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CORRIGENDUM TO VOL. 62.

Page 775, col. 1, line 2: *For* "Monlwade" *read* "Monlerade."

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INAUGURAL ADDRESS

By Dr. ALEXANDER RUSSELL, President.

(Address delivered before THE INSTITUTION, *18th October,* 1923.)

In this address a few comments are first made on the work of this Institution. A very brief survey is then given of the progress of electrical engineering since the War. Finally one or two scientific and engineering subjects in which I am specially interested are discussed.

THE INSTITUTION OF ELECTRICAL ENGINEERS.

We naturally take pride in our connection with this Institution and, through it, with the many electricians who have advanced our knowledge and applied electrical science so successfully to ameliorate the conditions of human life. Special mention must be made of Lord Kelvin and Alexander Graham Bell. Both made many inventions and founded new industries, and both are universally regarded as benefactors of humanity.

Concurrently with the phenomenal increase in our numbers we have kept in close touch with all parts of the kingdom by means of our Local Centres and Sub-Centres. Through the *Journal* our overseas members learn of the progress that we make and of the difficulties that we encounter. The Institution unites the workers in all branches of the electrical industry for mutual help and encouragement. It has always taken a leading part in the vanguard of electrical research. It takes a special interest in engineering education, recognizing that a thorough understanding of physical principles and a sound knowledge of the latest engineering developments are essential to progress.

As in duty bound, it honours all the great electricians. Its library contains many very valuable pamphlets and books which are at the disposal of engineers of every nationality. In addition to its functions as a storehouse of knowledge it does its utmost, by means of its Benevolent Fund, to assist to be self-supporting those who have fallen on evil times.

It has always been our policy to keep in close touch with our sister Institutions. Recently an advisory body founded by the Institutions of Civil, Mechanical and Electrical Engineers, and by the Naval Architects, has been formed. It is called the Engineering Joint Council. So far as we are concerned it takes the place of the Conjoint Board of Scientific Societies which has now been disbanded. It is hoped that this organization will be a help in advancing our joint interests.

Forty years ago this Institution co-operated with the Royal Meteorological Society, the Royal Institution of British Architects and the Physical Society of London in investigating the methods of protecting against damage by lightning. This Lightning Rod Conference published a valuable report in 1882. Sir Oliver Lodge, in a paper read before this Institution in 1889, showed that advances in our knowledge made it essential to alter several of the recommendations made by the Conference. Recent advances in meteorology have again revived interest in the matter. Some of the problems in connection with it are discussed later.

We are making arrangements for closer co-operation with the American Physical Society and with the Physical Society of London in producing the Physics Section of *Science Abstracts*. From every point of view this co-operation is highly desirable and we welcome it.

TRANSATLANTIC RADIO-TELEPHONY.

During last year satisfactory progress has been made in the development of transatlantic radio-telephony. It has been proved experimentally that under favourable weather conditions telephony between New York and London is perfectly satisfactory. The results published show that there are very large daily variations in the audibility and also very large seasonal variations. The assumption that the daily variation is due to the difference in the absorbing qualities of the atmosphere in daytime and night-time leads to results which agree well with the experiments. The latest results indicate that it will be necessary to use a wave-length greater

than 5 000 metres if the best voice transmission is to be obtained.

Broadcasting.

In the United States there were no fewer than 581 licensed broadcasting stations on July 2nd. But of this number about 25 per cent had ceased to operate. The reasons for their stoppage are mainly financial. In very few cases has the service been discontinued owing to a lack of appreciation by the public. In this country we have only one organization for broadcasting and it has made good progress during the past year. It is certain that, in the future, broadcasting will have an important effect on national development.

The Electric Lighting Industry.

Since the termination of the War in 1918 the section of the industry which deals with the supply of electrical energy has been very active and real progress has been made. Although during the War years, power stations had to be extended hurriedly so as to cope with the normal growth of the load, yet many of them were prohibited from getting the necessary new plant. They had therefore to run under overload conditions. Only repairs which were absolutely necessary were made. The result of this was that in the beginning of 1919 many schemes were under consideration either for the overhaul of existing or for the purchase of new plant.

During 1920 and 1922 the prices of engineering materials were very high. This naturally hindered development. Now that prices are falling to values approaching pre-War level, a large amount of generating machinery is being installed in all parts of the country. In 1920 official sanction was given for the installation of generating plant aggregating 500 000 kilowatts. In 1921, for the reasons stated above, this figure fell, but in 1922 it nearly reached the same value. Since the War several very large generating stations have been built and several others are in course of erection.

Boiler house.—In the boiler house radical developments are taking place. The possibilities of pulverized fuel are being thoroughly investigated both in this country and in America. The changes which have been made and which it is proposed to make in the working pressure of the steam would seem incredible to the older generation of engineers. The working steam pressure was gradually raised from 160 to 250 lb. per square inch. Now steam pressures of 350, 450 and even 500 lb. per square inch are not uncommon. The new station * of the Edison Electric Illuminating Co. of Boston will have boilers supplying steam at a pressure of 1 200 lb. per square inch to a 2 500-kW high back-pressure turbo-generator. The exhaust steam is reheated to 700° F. and then enters a second turbine which is of ordinary construction.

We know that as the temperature in a boiler rises the density of the water in it diminishes and the density of the steam in it increases owing to the increased pressure. When the critical temperature of 705° F. is attained the steam and water have the same density and are indistinguishable from one another. At this temperature the pressure is roughly 3 200 lb. per square inch. The water also, having no latent heat, passes quietly into the gaseous state. The English Electric Co., in association with the Benson Engineering Company of London, are making experiments at the present time * to generate steam at about 3 200 lb. pressure per square inch which, after being throttled to 1 500 lb. per square inch by means of a reducing valve and its temperature raised to about 700° F., will be used to drive a specially constructed 350-kW turbine. After being expanded in this turbine the steam will be reheated and passed at a pressure of 250 lb. per square inch to a low-pressure turbine which will be of ordinary make. That difficulties will be encountered in the manufacture of these very high-pressure turbines is certain. That economies would result from their use is equally certain. Increasing the steam pressure will secure a higher thermodynamic efficiency. It will also have the advantage of reducing the size of the steam pipes. The pioneers of the method are to be congratulated on their courage and their foresight.

Engine room.—In the turbine room the size of generating plant continues to increase. In 1918 a 6 000-kW set was considered a large unit. To-day a standard size is 15 000 kW. Several sets of 25 000 kW are in operation and in a London station now being built 35 000-kW sets are being installed. Messrs. C. A. Parsons & Co. of Newcastle are constructing a 40 000-kW set for the Commonwealth Company of Chicago, and a 60 000-kW set is being built in America.

The use of these larger sets, with the corresponding increase in the total capacity of the modern power house, has led to great improvements in switchgear. As such switchgear under modern conditions may be called on to break over a million kilowatts and under such circumstances is subjected to enormous mechanical and electrical stresses, much still remains to be done in safeguarding it from damage. The British Electrical Research Association has the problem in hand and is carrying out a series of tests on switchgear which are likely to yield important results.

Since 1918 the thermal efficiency in large power stations has almost doubled. Five years ago the ratio of the heat equivalent of the kilowatts generated to the heat equivalent of the fuel consumed, that is, the thermal efficiency, was commonly only about 10 per cent. To-day there are power stations in different parts of the country with a thermal efficiency of 18 per cent. An efficiency of 25 per cent may be attained in the not very distant future.

Power transmission.—For the transmission of electrical energy over considerable distances the use of pressures of 6 000 and 11 000 has given place to pressures of 33 000 and 66 000 volts. The cable makers of this country are to be congratulated on their successful solution of the problem of making underground cables suitable for 66 000 volts. The number of overhead lines for transmission over long distances and for transmitting energy over scattered rural districts is rapidly increasing. There are, however, indications that for power transmission in country districts cheaper systems of underground cables using 11 000 and 22 000

* *Journal of the American Institute of Electrical Engineers*, 1923, vol. 42, p. 799.

* *English Electric Journal*, vol. 2, p. 229.

volts respectively will become common. Where a single-phase system of supply is used these methods will compare favourably as regards cost with overhead lines.

Polycore cables.—The use of polycore cables for a working pressure of 33 000 volts is becoming general in large industrial areas and in cities. At a few stations, where the loads justify it, higher working pressures are used or are on the point of being used. When polyphase systems are employed there is still, unfortunately, a difference of opinion as to whether it is more advantageous to use a polycore cable or single-core cables. The leading cable manufacturers are prepared to guarantee three-core cables up to 66 000 volts, and there are already a few of these cables in use.

The supply authorities in this country favour three-core cable as it is easy to handle. In Paris a three-phase system of 60 000 volts is in operation using single-core cables. No unexpected difficulties have arisen. A very real advantage of the Paris system is that all faults are faults to earth. Hence by putting a suitable impedance coil in the earth connection it is possible to restrict the fault current to a definite value. Hence an accidental fault gives no harmful shock to the supply system.

In the United States and Canada, where electricity is in more general use than in this country, there is a demand in the great industrial cities for cables which will withstand working pressures of at least 100 000 volts. Manufacturers are seriously considering the construction of short feeders for 100 000 volts as a commercial experiment. In a few years' time the question of using these very high pressures will have become one of great urgency in this country owing to the rapid increase in the load. Should, however, the supply engineers decide on their immediate use it will be necessary to use single-core cables.

Throughout Holland 50 000 volts has been adopted as the standard pressure for primary power transmission. Overhead transmission in conjunction with underground cables is in general use. It is interesting to notice that in several cases both three-core and single-core cables are used simultaneously. Data which will enable a practical comparison of their relative merits to be made will therefore soon be available. The three-core cables are of British and the single-core cables are of German manufacture.

Broadly speaking, we may say that the delay in the adoption of higher working pressures in this country and the delay consequently in securing the economies associated with them are due mainly to the absence of an effective national policy which would secure the harmonious working of the various supply stations so as to obtain the maximum economy. The Electricity Commission is doing everything in its power to obtain this desirable end. The developments that have taken place since the war, and their resulting economies, are reflected in the gradual lowering of the price of electricity to the consumer.

British Electrical Manufacturing Industry.

The closing of the mid-European and Russian markets to British products has been a severe handicap to the manufacturing industry. It has, however, been lessened by the increased demand from the overseas portions of the British Empire. It is satisfactory to notice that the exports of electrical machinery to British Dominions have increased and are continuing to increase. Judging from the steady improvement which has taken place during the past five years, there is every reason to regard hopefully the future position of the British electrical manufacturing industry.

The British Empire Exhibition.

The section of the British Empire Exhibition devoted to electrical manufactures embraces the most representative and impressive examples of electrical machinery and apparatus ever shown in this or any other country. Arrangements have been made for demonstrations of long- and short-distance radio-transmission, the very latest appliances being shown in operation. The plant of the power station, the value of which is £150 000, has been lent by the members of the British Electrical and Allied Manufacturers' Association (the B.E.A.M.A.) to the Exhibition for only a small fraction of its value. The Electrical Development Association is giving a very interesting exhibit which will show visitors the advantages of the domestic and small power applications of electricity.

World Power Conference.

In co-operation with our Institution, and with other scientific and technical Institutions, the B.E.A.M.A. is promoting a World Power Conference. The advantages of such a Conference are many, and keen interest is being taken in it by practically every civilized country. Committees have been formed representing the Dominion of Canada, the United States, America, France, Belgium, Italy, Norway, Sweden, Holland, Denmark, Greece and Czecho-Slovakia.

The Electrical Installation Industry.

The electrical installation industry to-day is prosperous. The quality of the materials used has never been better and the standard attained has never been higher. This is due to the good work done by the Institution in the production and continual revision of its Wiring Rules, and to the activities of the Electrical Contractors' Association. The British Engineering Standards Association by standardizing materials has helped to stabilize the industry. The National Industrial Councils also have done excellent work in fostering the good feeling which exists between employers and employed at the present time.

The Lamp-making Industry.

Immediately after the War the lamp makers embarked on a broad policy of extension and co-ordinated research work. The benefits of this policy are already seen in the great improvements that have been made in the manufacture of incandescent lamps. An immense amount of research work has been expended on the gas-filled lamp. Its universal adoption will greatly raise the standard of illumination. In the factory this

will lower the risk of accident, increase very appreciably the output and do much to prevent industrial fatigue.

Not many years ago the number of electric lamps used per head of the population of this country was the same as the corresponding number in the United States. Now the latter number is more than four times the former. I am glad, therefore, that the lamp industry is bringing the numerous advantages of a higher standard of illumination to the notice of the public.

Post Office Automatic Telephony.

The British Post Office, having had experience of the successful and economical working of 17 automatic exchanges in public service in this country, has decided that in the future this type of equipment shall be adopted in all important areas. Several of these exchanges are being constructed in the provinces, and contracts have been placed for others.

The difficult problems suggested by automatic working in the largest cities which have been under consideration for a lengthy period have now been solved. Arrangements have been made for the introduction of automatic switching in London. It is anticipated that the installation of several important automatic exchanges in the Central District will be commenced in 1925.

Long-distance Communication.

On 17th March, 1921, Sir William Noble outlined the use of light-gauge coil-loaded cables with thermionic repeaters. Great progress has since been made in their adoption. Cable routes have been completed between London, Derby and Manchester, London and Brighton, and London, Portsmouth and Southampton. Others which are approaching completion are London to Bristol, Bristol to Birmingham, Birmingham to Manchester, and Leeds to Hull. Several important extensions of existing routes are well in hand and several additional routes will shortly be commenced.

The rapid expansion of traffic between Great Britain and the Continent has rendered it necessary to consider the adoption of a type of submarine cable capable of carrying a larger number of channels than those at present in use. The manufacture for the Anglo-Dutch telephone service has therefore been commenced of a paper-core, lead-covered and continuously loaded cable.

Developments in Radio-Telegraphy in the Post Office.

The main trend of recent progress in radio-telegraphy has been in the direction of improvements in methods of transmission by the elimination of harmonics and impurities, and development work in connection with high-power radio transmitters using silica valves and water-cooled metal valves.

As the result of successful experiments on the use of a coupled circuit on an arc transmitter at the Northolt station, a similar circuit is now being installed at the Leafield station supplementary to the 250-kW arc installation. Very marked improvement has been effected in the suppression of harmonics and other undesirable emissions by the introduction of these circuits.

Valve transmitting sets producing 40 kW in the aerial have been assembled and operated using both silica valves and water-cooled metal valves. The most powerful valve which has proved commercially satisfactory is capable of producing 14 kW of high-frequency power in an oscillatory circuit. As the result of experimental work, valve transmitters are to be used in the new high-power station now in course of erection at Rugby. This station rated at 1 000 kW is designed to deliver 500 kW to the aerial circuit. The height of the masts for this station is to be 820 feet. Eight are now being erected and the site is so arranged that extensions up to twice that number can be carried out.

Railway Electrification.

The problem of railway electrification presented many almost insuperable difficulties in the past. The necessity for costly experiments and the difficulty of getting the requisite capital made engineers proceed cautiously. It has to be remembered also that steam railways were built with an eye always to the needs of the locomotive. It was only when railway engineers saw that it was the best way of overcoming the difficulties connected with urban and suburban traffic or of long tunnels or steep gradients that they adopted electric traction. The outlook at the present time is much more promising. Large orders for the extension of the electrification of railways in New Zealand, Australia, South Africa, Brazil and Japan have been received in this country and are very welcome to manufacturers. Electric traction engineers and manufacturers are looking forward to a busy future. With the high pressures now available for transmission and the use of automatic substations there is no technical reason why the whole of our railway systems should not be electrified. One benefit will be the diminished inroads on the limited stores of coal in our mines on which posterity has some claim. Mr. Roger T. Smith * has calculated that if the railways of this country were electrified there would be a saving effected of about 50 per cent in the quantity of coal consumed.

Research.

Combined research has much to place to its credit. The British Electrical and Allied Industries Research Association has broken much new ground and obtained interesting and important results. The opening of the Research Laboratories of the General Electric Co. at North Wembley is an excellent augury that the importance of scientific and commercial co-operation will soon be recognized by every leader of industry.

I should like to emphasize that our progress depends very largely on the work of the rank and file in the industry. It especially depends on those who make new inventions or perfect old methods. Our late President, W. Duddell, used to say that we could advantageously do much more than we are doing to encourage those who have made small inventions or discoveries. In particular he advocated that we should publish, in our *Journal*, accounts of any advances that

* Presidential Address to the British Section of the *Société Des Ingénieurs Civils de France*, 10th October, 1923.

had been made, no matter how short the paper was in which they are described. Some improvements may seem trifling to many and some may appear almost self-obvious. As, however, they may cheapen the cost of production and improve the quality and efficiency of our manufactures, they are of the highest value from the point of view of our national prosperity.

Kelvin Centenary.

On the 26th of June next we shall be celebrating the centenary of the birth of the greatest of our Past-Presidents, Lord Kelvin. It is only 16 years ago since some of us attended his funeral in Westminster Abbey, where he was buried with all the honours due to a prince of science. The greatest of natural philosophers since Isaac Newton, he had the power, rare amongst scientists, of completely realizing his conceptions in practice. We honour him specially for what he did to advance electrical knowledge. From the time when he was a student at Cambridge calculating the attractions between electrified spheres, down to the speculations he made about electrons in the latest years of his life, he was ever looking with eager eye to discover Nature's secrets.

Relativity.

A teacher is asked many questions about the theory of relativity. I am afraid that however much he has tried to understand this theory his answers will give little satisfaction. The Michelson-Morley experiment appears to show that the velocity of light is independent of the velocity of the earth. This is a very hard and a very disturbing statement. Luckily Fitzgerald showed us a way out. We are forced to conclude that the measuring rod has contracted by the two-hundred millionth part of its length in the direction in which the earth is travelling. A possible explanation of this is that the atoms forming the rod contain electrons. These electrons move with the rod and therefore act like electric currents. Theory shows that the mutual action of these currents would shorten the rod in exact accordance with the observed law.

We must remember that when Copernicus stated that the sun was stationary and the earth moved round it, he was derided by the upholders of the fixed earth theory. It is necessary therefore to be careful not to belittle Einstein's theory. It has nothing whatever to do with the mathematical suggestion of four dimensions in space for the existence of which not the slighest evidence has ever been advanced. Einstein discovered that our conceptions of the framework of space and time were at fault as we had neglected the fact that we were on a moving globe. The four dimensions in his theory are the three in space and one in time, and his results show that these four dimensions are not independent. The theory has been applied in astronomy and is also used in atomic theory. Unless, however, an engineering student has exceptional mathematical abilities he can employ himself more profitably by studying theories more directly applicable to our everyday life.

Atomic Theory.

On 15th January, 1891, Sir William Crookes gave an epoch-making Presidential Address to this Institution. It was entitled "Electricity in Transitu; from Plenum to Vacuum." He showed electric discharges in tubes exhausted to a high vacuum by powerful air pumps. He pointed out that the discharges acted as if they consisted of streams of negatively charged particles. A few years later Sir Joseph Thomson proved that these negatively charged particles were exactly the same from whatever gas they were obtained. They were in fact the atoms of which a negative charge of electricity is made up.

There is strong evidence that these electrons form part of every atom of matter. Sir Ernest Rutherford * recently described to us his theory that the atom consists of a nucleus surrounded by planetary electrons. The nucleus contains sufficient positive electricity to neutralize exactly the sum of the charges on the negative electrons. The atomic number of an element, which has introduced great simplifications in theory, is simply the resultant charge on the nucleus. The atomic numbers range from 1 to 92, so that we can infer that there are 92 different kinds of atom which could be distinguished by their chemical reactions. There are, however, only two different kinds of electrical atoms, the positive one which is the nucleus of the hydrogen atom, often called the proton, and the negative one called the electron. The assumption is made that all the different kinds of atoms are built up of protons and electrons. If these electrical atoms had been known to the scientists of 60 years ago, electrical progress in several directions would have been much accelerated.

Thunderstorms.

A remarkable thunderstorm visited London on the night of July 9–10, 1923. The storm appeared on the south coast and progressed W.N.W. at a speed of about 25 miles an hour, travelling through London, Bedford and Hull. The main rainfall, which was torrential in places, extended over a belt about 30 or 40 miles wide. The lightning flashes in some places occurred with only a few seconds' interval for hours at a time. The discharges were mainly from cloud to cloud or from a cloud to the upper air, and so the damage done was not serious.

It will be useful to consider the physics of the problem. In a Royal Institution lecture on 18th May, 1860, Kelvin† reminded his audience that many years previously Beccaria with very insensitive instruments had made many records of atmospheric electricity. He suggested that now that accurate instruments are available careful records should be made. He wanted to know in particular how electricity was distributed in fine weather in the strata of the atmosphere up to a distance of 6 miles. He pointed out that this could easily be done by means of balloon observations. He wanted to know also whether the particles of rain, hail and snow possessed charges of electricity.

To picture what happens more clearly I shall

* *Journal I.E.E.*, 1922, vol. 60, p. 613.
† See "Reprint," p. 268.

describe some of the additions made to our knowledge during the last 25 years by meteorological science. From data published by the Meteorological Office we find that in the south-east of England if the temperature of the air at the earth level be 10° C., then as we go vertically upwards it falls uniformly for a distance of 6 miles where the temperature is only about − 53° C. After this altitude is attained the temperature, curiously enough, remains almost practically constant up to the greatest height reached by pilot balloons, which is about 12 miles. The layer of the atmosphere up to 6 miles high is called the troposphere. Above this is the isothermal layer called the stratosphere. Clouds only appear in the troposphere. There is very little moisture in the stratosphere. For example, practically no snow falls on the top of Mount Everest; the snow on it is blown up from lower down the mountain.

On a calm day as we go upwards the electric potential gradient diminishes. In midsummer a usual ground value is of the order of 100 volts per foot. In mid-winter the average ground value is at least twice as high. In foggy weather it is sometimes greater than 500 volts per foot. In fine weather the potential difference between the ground and the top of the troposphere is of the order of a million volts, and above this the potential gradient is practically zero, and so the isothermal layer is also an equipotential layer. This voltage between the earth and the equipotential layer is, however, much too small to produce a lightning flash. That requires at least thousands of millions of volts.

The surface of the earth is generally at negative potential but it sometimes has a small positive potential. Owing to the vertical potential gradient, the electrons from the earth are always moving skywards and act like a vertical earth-air current. Sir Francis Ronalds,* one of the early members of this Institution, made observations at Kew Observatory for the British Association. He found that the intensity of the atmospheric electrification had a maximum value every morning and another maximum value in the afternoon. Chree† has shown that these maxima values are usually greatest in cold weather. Possibly, therefore, they may be due to smoke or other impurities in the atmosphere.

The following table may be taken as roughly typical of the temperature, pressure and electric strength of the atmosphere at various heights above the ground up to 12 miles. The ground temperature and pressure are supposed to be 15° C. and 760 mm of mercury respectively.

Height in miles	Temp., Cent.	Pressure in mm	Electric strength in kV per cm‡
0	15	760	28
3	− 15	412	17
6	− 50	206	10
9	− 50	96	4·6
12	− 50	44	2·1

The table shows that at a height of 3 miles the temperature is below the freezing-point and the electric strength of the air is only about half what it is at the surface of the earth. At a height of 24 miles the barometric pressure would only be about 2·4 mm and the electric strength would only be of the order of some hundreds of volts per centimetre. At some height, probably about 30 miles vertically up, the electric strength would attain a minimum value. At greater heights it would begin to increase very rapidly and soon become at least 30 times greater than the electric strength of air at ground-level.

J. L. R. Hayden* placed two 1-cm spheres in a kenotron bulb at a distance of 0·3 cm apart. At atmospheric pressure the disruptive potential gradient was 47 kV per cm, but with an excellent vacuum a gradient of 1 235 kV per cm was required to break down the gap. A good vacuum therefore has an electric strength at least 26 times the strength of air at ordinary pressures.

In a recent paper† F. W. Peek has shown that a much higher impulsive voltage, that is, a voltage similar to that which causes Lodge's B flash, is required to spark over a given distance than a voltage at ordinary working frequencies. He also shows that some substances which act as conductors at working frequencies can be punctured by impulsive voltages. For instance, he found that an impulsive voltage of 149 kilovolts broke down the gap between two 1-in. spheres, immersed in water, at a distance of 1 inch apart. The conducting water therefore acted as if it were a dielectric having an electric strength between three and four times that of air.

It is easy to get a discharge from an electrode to the surface of water. The author remembers once being in a small boat on the sea on a perfectly calm day during a thunderstorm. Where the lightning struck the sea a narrow column of spray, or more probably steam, seemed to rise suddenly not unlike the splash made by a gannet when diving. Possibly when a flash of lightning strikes sandy soil and forms a fulgurite, vapour or smoke might be observed.

When it is considered that two million volts will only bridge a few feet in air, the voltage of a lightning flash to earth must be exceedingly high. We can conclude from laboratory experiments that the electric resistance of fog or mist is greater than that of clear air, but that its electric strength is much the same.

Let us now consider very briefly the mechanism of a thunderstorm. Owing to the small potential differences produced by the ordinary earth-air electric current, and consequently the minute amount of electrostatic energy stored in the field, we are justified in assuming that the most important function of this current is in assisting to start the storm. A thunderstorm usually travels over considerable distances and keeps on generating prodigious quantities of electrical energy. It functions like an electrostatic machine

* Cf. W. Snow Harris: "Rudimentary Electricity," 1848.
† *Philosophical Transactions*, vol. 206, p. 299.
‡ By the electric strength of air we mean the maximum electric stress it would withstand between two very large spheres at an appreciable distance apart. The numbers given at the greater heights are only roughly approximate.

* *Journal of the American Institute of Electrical Engineers*, 1922, vol. 41, p. 853.
† *Ibid.*, 1923, vol. 42, p. 623.

driven by a very powerful motor. We have to consider what produces the energy which the lightning flash converts into heat, light, sound and radio waves. Aviators and balloonists report that the air in the centre of a thundercloud is practically always moving upwards with considerable velocity. In the upper layers of the troposphere, owing to ionization, there are sometimes many free electrons. If the humidity of the upward current of air be high enough the vapour condenses round the electrons and so the air is full of minute globules of water. Some of these coalesce together forming larger drops. If the vertical velocity of the air be greater than 8 metres per second (17 miles per hour) the large drops as they are blown upwards often break into smaller drops. Experiment shows that the charge on the smaller drops is generally negative and on the larger drops positive. As the larger drops are often kept oscillating in the higher and very cold strata of the atmosphere owing to fluctuations in the velocity of the air currents, they keep melting and freezing again, producing ordinary hailstones. As the gusts vary we have the large drops and hailstones positively charged descending downwards. Electrical energy, due partly to the work done by gravity on the descending drops and by the air currents on the ascending drops, is stored in the atmosphere. On the upper part of the cloud we have a negatively charged layer and on the lower part a positively charged layer. The falling drops keep increasing the potential difference until it gets so high that a disruptive discharge ensues.

I have imagined the cloud to be bipolar. Several kinds of electric discharge can therefore ensue. We may have brush discharges between the upper layer and the better conducting layers higher up. Some kinds of sheet lightning could be caused in this way. On a summer evening it is not very unusual to see sheet lightning in broad flashes coming from a cloud and ending in the upper air. An ordinary flash also has sometimes been observed to end in clear air. If another cloud drifts up we may have a flash between the upper layer and this cloud. We may have flash discharges between the lower layer and the earth or another cloud. Possibly also we may have a flash-over between the two poles of the thundercloud when they are not too far apart. C. T. R. Wilson* describes this phenomenon by saying that the cloud may be short-circuited.

Operations of this nature happen during a thunderstorm. The separation of the charged drops due to the difference in their velocities produces high potential differences. There is plenty of energy available. The work done by an inch of rain falling a mile is 27 500 ft.-lb., or the one-hundredth part of a kilowatt-hour, per square foot of the earth's surface. It has recently been shown that in general the purer† the raindrops the greater are the electric charges they assume on pulverization. In particular any contamination of a raindrop with sodium chloride diminishes the charges produced when it breaks in air. This possibly has the effect of diminishing the intensity of thunderstorms at seaside towns. It has been suggested that the introduction of ammonia into the upper layers of the atmosphere would hinder the development of a thunderstorm. To utilize this practically, however, could rarely be attempted, as a thunderstorm usually covers a large area.

What we as engineers are specially interested in is how to protect buildings and apparatus and power and communication lines from damage due directly or indirectly to lightning flashes or to the gradual accumulation of electric charges. I think that there is no need to call a second Lightning Rod Conference. The principles laid down by Sir Oliver Lodge* in this Institution in 1889 still hold good. They have been adopted by the Lightning Research Committee of the Royal Institute of British Architects.† In practice they are found quite satisfactory.

We now know that a lightning discharge is unidirectional although it may be rapidly pulsatory. But even a unidirectional discharge gives rise to an alternating current in line wires, and may give rise to alternating currents in lightning conductors. The wires in insulated conductors have been found broken into small pieces by a lightning discharge. This seems to point to rapidly alternating currents. Lodge's A and B flashes of lightning are known to all students of electrical engineering. The B flash, which is the dangerous one, is also referred to as an impulsive discharge. I think that possibly too much stress is laid on the importance of having a low resistance to earth of a lightning rod. About 25 years ago I measured the resistance to earth of the conductor of a large chimney stack. It came to 70 ohms. As the end of the conductor was buried in coke I had it dug up to examine the earth plate. This was found to be a brick placed there 20 years previously by the workman who erected it. I was told that the conductor had several times been struck by lightning and acted quite satisfactorily. I have noticed that workmen before the test is made sometimes pour a pail of water on the spot where the conductor enters the ground. Possibly they think that a high earth resistance is a reflection on the way they perform their duties.

Difficult problems sometimes arise. I remember once considering how to protect a very large iron water tank supported by iron pillars on the summit of a hill and naturally making an excellent earth through the water pipes at its centre. As the outside iron pillars were embedded in concrete it was throught advisable to connect them directly to earth by means of earth plates.

I think it highly desirable that records of curious lightning phenomena should be kept. In the eighteenth century this was done; the *Philosophical Transactions* of the Royal Society before 1800 contain very many interesting records. If we knew exactly the mechanism of thunderstorms the need for recording unusual phenomena would not be so urgent. Faraday was very doubtful about the existence of globular lightning. In his "Experimental Researches," vol. 2, p. 525, he says: "It is more than doubtful that they have anything to do with atmospheric electricity or lightning."

* "Atmospheric Electricity," Glazebrook's D.A.P., vol. 3.
† T. T. Nolan and H. V. Gill, *Philosophical Magazine*, 1923, vol 46, p. 226.

* *Journal I.E.E.* 1889, vol. 18, p. 386; or Lodge's "Lightning Conductor and Lightning Guards."
† *Journal of the Royal Institute of British Architects*, 1904, vol. 12, p. 405.

Even W. J. Humphreys in his recent excellent book on the "Physics of the Air" says: "Doubtless many reported cases of ball lightning, probably the great majority, are entirely spurious, being either fixed or wandering brush discharges or else nothing other than optical illusions due presumably to persistence of vision." After these weighty statements I now give my own experience.

Many years ago when I was on the coast of Ayrshire on the west side of Scotland, I saw what I consider to be globular lightning. Although the visibility was very fair there was a curious haze higher up. The ground potential gradient was probably high. Suddenly two spheres of incandescent gas of a dull reddish colour about 20 or 30 feet up moved slowly in from the sea. They were each about a foot in diameter. One of these hit the wall of a building but did no apparent damage although it made a loud report and considerably startled the inhabitants. The other drifted away.

I consider that the evidence in favour of globular lightning is overwhelming. Witnesses testify to seeing it, to hearing it burst, to finding small metal objects melted by it and even to seeing people killed by it. I shall confine myself to describing two typical cases. The first case I take from the *Philosophical Transactions* of the Royal Society for 1781, p. 42. At Eastbourne the tenant of a large three-story house facing the sea was standing and looking through the window at an ominous black cloud. He saw several balls of fire drop successively out of the cloud into the sea. Suddenly he was violently thrown backwards by what he described as a flash of fire. Many people outside the house at that instant saw something which in form and flame they all agreed was like an immense "sky rocket" strike the house. The tenant's clothes were torn and pieces of metal he had about him were melted. Every pane of glass in the room was completely smashed. On the ground floor the coachman and a footman were killed and on the top floor a lady and her maid were rendered insensible. All the bell wires in the house were deflagrated.

The second case is similar to many others.* It is described by a sergeant† of H.M. 96th Regiment which was stationed at Dum-Dum near Calcutta in 1879, where the phenomenon occurred. The ball of globular lightning first passed over a bathing tank in which seven men were bathing. It went right through the first floor of one barracks, making one man insensible. Going out of a window it passed down the wall, moved over the end of the barrack square and then climbed up to the roof of the next barracks, knocking off a projecting rain-water pipe. Finally it went down a zinc ventilating pipe where it burst with a loud report, killing a soldier who was sitting on his bed directly underneath. A current passed down the punkah wire, setting the punkah on fire. Much damage was done to the victim's rifle, parts of it being melted. Three of the men bathing were rendered temporarily deaf. Many other very similar instances could be given, the undesigned coincidences in which, as Paley would say, are very convincing.

* "Phénomènes Électriques de l'Atmosphère": Gaston Planté, 1888.
† *The Builder*, Oct. 26, 1896, p. 359.

Globular lightning seems to be a brush discharge taking place at the end of a column of air of higher conductivity than the neighbouring air. The difficulty in accepting this explanation, however, is in seeing how the conducting column can go through rooms and yet provide sufficient energy to the globe a considerable distance away to do serious damage. In certain cases, however, it may possibly get its energy from the atmosphere by another path when it bursts.

A Clear Atmosphere.

Engineers are accustomed to think of light waves and Hertzian waves as travelling in straight lines. They were therefore surprised when it was found that Hertzian waves travel round the earth. This is generally explained by supposing that the radio waves are successively reflected by certain conducting layers of the upper atmosphere and by the surface of the earth or sea. Since light waves only differ from radio waves in wave-length we should expect, when the atmosphere is exceptionally still and clear, to be able to see round the curvature of the earth. An interesting case where the spectators could see over 400 miles occurred on the 2nd of May last. Colonel Neame, V.C., and Mr. F. S. Smythe, an electrical engineer, were climbing the Finsteraarhorn in the Bernese Oberland. The weather was perfect and the visibility extremely good. On a rock ridge at an altitude of 13 800 feet they could see the Black Forest 150 miles to the north and the snow-capped peaks of Italy over 100 miles to the south. What they next saw I shall tell in Colonel Neame's own words taken from a letter to *The Times*.

"Suddenly at 11.55 a.m., the image of a ship appeared in the sky just to the east of the Eiger Peak, floating in a blue shimmer just beyond the visble horizon. This lasted for a minute or so and then vanished. Very soon after a line of five ships appeared further east, funnels and masts clearly distinguishable. This image lasted for some 15 minutes and varied in its clearness from time to time. The ships of course appeared greatly exaggerated in size and were the right way up and not inverted. The nearest sea in this direction was the English Channel 400 miles away."

As, at the height they were, the visible horizon was only some 140 miles away, the light must have been bent round the curvature of the earth. A mirage seen over this distance must be a very rare phenomenon. It was probably caused by the refraction of the light rays by the strata of the atmosphere and these strata must have been very sharply defined. As radio and light waves only differ from one another in wave-length we can infer with certainty that radio waves can be refracted in the troposphere so as to bend round the earth. In certain cases also they can be reflected by damp earth, the sea or the dividing surface between two strata. In addition to reflection and refraction, however, the radio waves are scattered at the dividing surface between two strata, and this scattering must play an important part in radio transmission. The assumption that there is a definite stratum of the atmosphere that always reflects radio waves seems unnecessary.

Mathematical Theorems.

In conclusion a few mathematical theorems are given which are of theoretical interest and may be of practical value. Brief discussions of them are given in the Appendix. The first theorem shows that the inductance coefficient per unit length of the current in one cylinder with the current in a second parallel cylinder, is not equal to the inductance coefficient of the current in the second cylinder with the current in the first cylinder except in the case when the two cylinders are equal to one another. For example, when we have two infinite parallel cylinders we cannot assume that they have a "mutual" inductance coefficient. In the case of a concentric main there is a mutual inductance coefficient between the outer and inner conductors when their axes are coincident. If the axes of the outer and inner conductor are parallel but not coincident there is no mutual coefficient. In these cases, however, it is proved that the effective self-inductance of the concentric main is independent of the distance between the axes. The values found for the inductance coefficients can be at once applied to find the effective inductance of a concentric main in which the inner or outer or both of the conductors are made up of individual wires.

The second theorem discussed is to find the position of the site of a power station when the feeding points are given so that the amount of copper required for the feeding mains may be a minimum for the given power loss in them. It is shown that if the current required at or near one of the feeding points is equal to or greater than the sum of the currents required at the other feeding points, then this is the site which makes the copper required for the mains a minimum. It will be noticed that this site is not the centre of gravity of the load.

The third problem discussed is that of the specification of wave shape for alternators. The deviation and harmonic factor methods are examined and found unsuitable. An easy method is suggested for finding graphically the effective value and the first and third harmonics of an alternating current wave from its oscillogram. If the effective value of the wave comes out equal to the amplitude of the first harmonic within the limits of the errors of observation and the ratio of the amplitude of the third to the first harmonic be sufficiently small, and if, in addition there is no obvious ripple on the wave, then it may be considered to be satisfactory. If there is obviously a ripple, the frequency of which can be measured, its amplitude can be readily found by applying a formula first given by Silvanus Thompson. Instead of finding the harmonics graphically from the oscillogram, in many cases it would be more convenient to find them experimentally by a resonance method.

The final problem discussed is that of specifying the power factor of a polyphase load. In single-phase working the numerical value of the load in watts, the value of the power factor and whether it is lagging or leading are sufficient to specify the load. In polyphase work, however, not only have we to consider the load and the power factor, but it is necessary to introduce another factor to measure the balance or the want of balance of the currents taken from the mains. For the same total load and average power factor we can have all kinds of loads more or less desirable. But if a balance factor is given in addition, then the nature of the load is specified much more definitely. A first attempt has been made to specify an unbalanced polyphase load. The author hopes that others will follow up and improve his suggestions.

APPENDIX.

1. The Inductance Coefficients of Cylindrical Conductors.

When electric circuits are completely separated from one another the ordinary definitions of self and mutual inductance apply. When, however, the electric currents have paths in common, as for instance the three mains of a three-phase system or the inner and outer conductor of a concentric main, there may be no "mutual" inductance coefficient between two of the conductors. That is, the inductance coefficient per unit length of one of the mains on the other may have a different value from the corresponding coefficient of the latter on the former.

We shall first consider the coefficients for two infinitely long, parallel, hollow cylindrical conductors (Fig. 1). Let the inner and outer radii of the cylinders

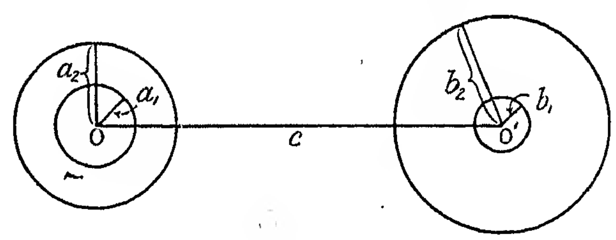

Fig. 1.

be a_1, a_2 and b_1, b_2 respectively. Let c be the distance oo' between their axes. Then if i_1 and i_2 be the currents in the conductors the linkages per unit length of the flux due to i_1 between the axis of the current i_1 and a concentric cylinder of radius $c + b_2$ may be written $L_{11}i_1^2$. If $i_1 + i_2 = 0$, the cylinders of the flux due to i_1 having a greater radius than $c + b_2$, being linked with $i_1 + i_2$, will add nothing to the total linkages. Similarly we can write the linkages of the flux due to the current i_1 with i_2 in the form $L_{12}i_1i_2$, neglecting the cylinders of flux the radii of which are greater than $c + b_2$. Proceeding as in Russell's "Alternating Currents" (vol. 1, p. 86), we find that

$$L_{11} = \frac{a_2^2 - 3a_1^2}{2(a_2^2 - a_1^2)} + \frac{2a_1^4 \log (a_2/a_1)}{(a_2^2 - a_1^2)^2} + 2 \log \frac{c + b_2}{a_2} \quad (1)$$

and $$L_{12} = 2 \log \frac{c + b_2}{c} \quad . \quad . \quad . \quad . \quad (2)$$

Similarly, when $i_1 + i_2 = 0$, we get by symmetry:—

$$L_{22} = \frac{b_2^2 - 3b_1^2}{2(b_2^2 - b_1^2)} + \frac{2b_1^4 \log (b_2/b_1)}{(b_2^2 - b_1^2)^2} + 2 \log \frac{c + a_2}{b_2} \quad (3)$$

and $$L_{21} = 2 \log \frac{c + a_2}{c} \quad . \quad . \quad . \quad . \quad (4)$$

Comparing (2) with (4) we see that $L_{21} = L_{12}$ only when $a_2 = b_2$.

The effective inductance, L, per unit length of the circuit formed by the two conductors is given by:—

$$L = L_{11} + L_{22} - L_{12} - L_{21}$$

On substituting and simplifying we get Maxwell's formula.*

In the case of solid wires, $a_1 = 0$, $a_2 = a$, $b_1 = 0$ and $b_2 = b$, and we get

$$\left.\begin{aligned} L_{11} &= \tfrac{1}{2} + 2 \log \frac{c+b}{a}, \quad L_{22} = \tfrac{1}{2} + 2 \log \frac{c+a}{b} \\ L_{12} &= 2 \log \frac{c+b}{c}, \qquad L_{21} = 2 \log \frac{c+a}{c} \end{aligned}\right\} \quad (5)$$

and $$L = 1 + 2 \log \frac{c^2}{ab}$$

As an example of the use of formula (5) let us find an expression for the electromagnetic energy stored up per unit length in three parallel cylindrical conductors, 1, 2 and 3 (Fig. 2), the radii of the conductors being r_1, r_2 and r_3 and the distance between their axes being a_{12}, a_{23} and a_{31}. We shall suppose that

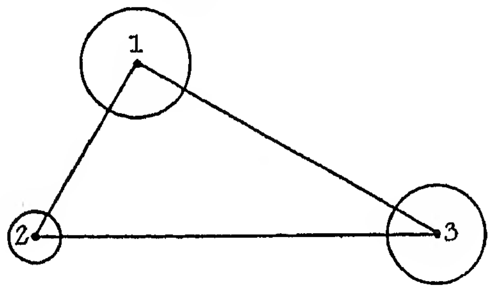

FIG. 2.

$i_1 + i_2 + i_3 = 0$. Then the energy stored in the field arising from the flux linkages due to i_1 is, if a_{13}, a_{23} and a_{12} are in descending order of magnitude, given by:—

$$\left\{ \tfrac{1}{2} + 2 \log \frac{a_{13} + r_3}{r_1} \right\} i_1^2 + 2 \log \frac{a_{13} + r_3}{a_{12}} i_1 i_2 + 2 \log \frac{a_{13} + r_3}{a_{13}} i_1 i_3$$

Writing down the other two components, adding them all together and noticing that

$$i_1^2 + i_2^2 + i_3^2 = -2(i_1 i_2 + i_2 i_3 + i_3 i_1)$$

we see that the energy W_m is given by

$$\begin{aligned} W_m = &\left\{ \tfrac{1}{2} + 2 \log \frac{a_{12} a_{13}}{a_{23} r_1} \right\} i_1^2 \\ &+ \left\{ \tfrac{1}{2} + 2 \log \frac{a_{23} a_{21}}{a_{31} r_2} \right\} i_2^2 \\ &+ \left\{ \tfrac{1}{2} + 2 \log \frac{a_{31} a_{32}}{a_{12} r_3} \right\} i_3^2 \end{aligned} \quad (6)$$

* CLERK MAXWELL, "Electricity and Magnetism," vol. 2.

This is true whatever are the relative values of the sides of the triangle.

In the ordinary balanced three-phase case we can write

$$a_{12} = a_{23} = a_{31} = a, \quad r_1 = r_2 = r_3 = r.$$
$$i_1 = I \sin \omega t, \quad i_2 = I \sin [\omega t - (2\pi/3)]$$

and $$i_3 = I \sin [\omega t - (4\pi/3)]$$

Hence $$W_m = \tfrac{3}{4}\left(1 + 4 \log \frac{a}{r}\right) I^2$$

which is an absolute constant independent of the time. Similarly if k_{11}, k_{12}, . . . be Maxwell's capacity coefficients and $e_1 = E \sin \omega t$, etc., we get

$$W_e = \tfrac{3}{4}(k_{11} - k_{12}) E^2$$

where W_e is the electrostatic energy. Hence on a balanced load $W_e + W_m$ has the same value at every instant. It is not easy to compute the value of $k_{11} - k_{12}$. As it equals double the capacity between any two of the mains it can, however, be very easily measured.

Let us now consider a hollow cylinder (Fig. 3) sur-

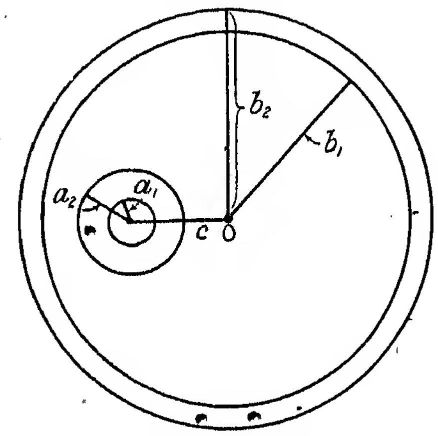

FIG. 3.

rounding another hollow cylinder, their axes being parallel but at a distance, c, apart. If the inner and outer radii of the inner cylinder be a_1 and a_2, and for the outer cylinder b_1 and b_2, $c + a_2$ being less than b_1, we get the result, assuming that $i_1 + i_2 = 0$ and proceeding as in Russell's "Alternating Currents" (vol. 1, p. 86), that

$$L_{11} = \frac{a_2^2 - 3a_1^2}{2(a_2^2 - a_1^2)} + \frac{2a_1^4 \log (a_2/a_1)}{(a_2^2 - a_1^2)^2} + 2 \log \frac{b_2 + c}{a_2} \quad . \quad . \quad (7)$$

$$L_{12} = 1 - \frac{2b_1^2}{b_2^2 - b_1^2} \log \frac{b_2}{b_1} + 2 \log \frac{b_2 + c}{b_2} \quad . \quad . \quad . \quad . \quad (8)$$

$$L_{21} = 1 - \frac{2b_1^2}{b_2^2 - b_1^2} \log \frac{b_2}{b_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

and

$$L_{22} = \frac{b_2^2 - 3b_1^2}{2(b_2^2 - b_1^2)} + \frac{2b_1^4 \log (b_2/b_1)}{(b_2^2 - b_1^2)^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

To get the effective self inductance, L, we have

$$L = L_{11} + L_{22} - L_{12} - L_{21}$$

On substituting the values of the coefficients and simplifying we get Rayleigh's formula * for the effective self inductance of two coaxial cylinders. We have thus proved the important result that the inductance of a circuit formed by two hollow, parallel cylinders one inside the other is independent of the distance between their axes. It is to be noticed that L_{12} is only equal to L_{21} in the case when the cylinders are coaxial. The value of L_{11} depends on c but the value of L_{22} is independent of c.

When the inner cylinder is solid, $a_1 = 0$, $a_2 = a$, and so $L_{11} = \frac{1}{2} + 2 \log \frac{b_2 + c}{a}$, the other coefficients remaining the same. Formulæ (1) to (4) and (7) to (10) enable us to write down the formulæ for polycore cables very simply, without the necessity of using formulæ for geometrical mean distances. Consider, for instance, an n-core cable (Fig. 4) the radius of

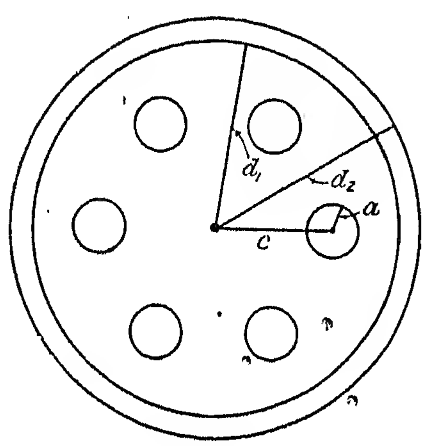

FIG. 4.

each core being a and the axis of each core being at a distance c from the axis of a hollow cylinder, of radii d_1 and d_2, by which we suppose the current returns. Let the current in each core be i, and let I be the current in the return cylinder, so that $ni + I = 0$. If a_{pq} denote the distance between the axes of the pth and qth core, we get by De Moivre's property of the circle:—

$$a_{12} \times a_{13} \ldots a_{1n} = nc^{n-1}$$

and, writing W for the electromagnetic energy,

$$\begin{aligned} 2W &= ni^2 \left\{ \frac{1}{2} + 2 \log \frac{d_2 + c}{a} \right\} + 2ni^2 \log \frac{(d_2 + c)^{n-1}}{nc^{n-1}} \\ &+ niI \left\{ 1 - \frac{2d_1^2}{d_2^2 - d_1^2} \log \frac{d_2}{d_1} + 2 \log \frac{d_2 + c}{d_2} \right\} \\ &+ niI \left\{ 1 - \frac{2d_1^2}{d_2^2 - d_1^2} \log \frac{d_2}{d_1} \right\} \\ &+ I^2 \left\{ \frac{d_2^2 - 3d_1^2}{2(d_2^2 - d_1^2)} + \frac{2d_1^4 \log (d_2/d_1)}{(d_2^2 - d_1^2)^2} \right\} \\ &= LI^2 \end{aligned}$$

where L is the effective self inductance of the whole circuit, and thus

$$L = \frac{1}{2n} + \frac{2}{n} \log \frac{c}{na} + 2 \log \frac{d_1}{c} - \frac{3d_2^2 - d_1^2}{2(d_2^2 - d_1^2)} + \frac{2d_2^4}{(d_2^2 - d_1^2)^2} \log \frac{d_2}{d_1} \quad . \quad (11)$$

We see that the effective self inductance is only independent of c when n is unity. When we can take $d_1 = d_2 = d$, the formula simplifies to

$$L = \frac{1}{2n} + \frac{2}{n} \log \frac{d^n}{nac^{n-1}}$$

In the case of a concentric main where the thickness of the outer conductor is very small compared with either of its radii, and $n = 1$, we have:

$$L = \frac{1}{2} + 2 \log \frac{d}{a}$$

and L is independent of c.

When $n = 6$, we have:—

$$L = \frac{1}{12} + \frac{1}{3} \log \frac{d^6}{6ac^5}$$

$$= -0 \cdot 5139 + 2 \log \frac{d}{c} + \frac{1}{3} \log \frac{c}{a}$$

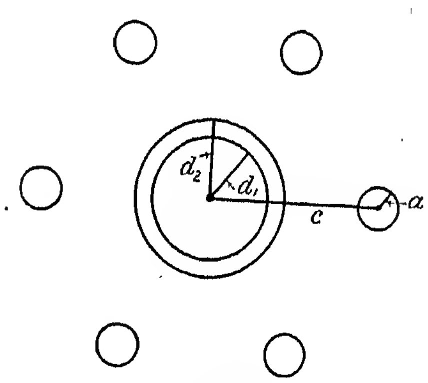

FIG. 5.

Similarly (Fig. 5) when the small cylinders are arranged symmetrically round the large one, we find that

$$L = \frac{d_2^2 - 3d_1^2}{2(d_2^2 - d_1^2)} + \frac{2d_1^4 \log (d_2/d_1)}{(d_2^2 - d_1^2)^2} + \frac{1}{2n} + \frac{2}{n} \log \frac{c}{na} + 2 \log \frac{c}{d_2} \quad . \quad (12)$$

where a is now the radius of the small cylinders and d_1, d_2 are the radii of the large inner cylinder. If $d_1 = 0$ and $d_2 = d$ we get

$$L = \frac{1}{2} + \frac{1}{2n} + \frac{2}{n} \log \frac{c}{na} + 2 \log \frac{c}{d} \qquad (13)$$

When n is unity, $L = 1 + 2 \log \frac{c^2}{ad}$, and, when n is very large, $L = \frac{1}{2} + 2 \log \frac{c}{d}$.

As a numerical example, put $c = 2$, $d = 1$, $a = \frac{1}{2}$, and

* Philosophical Magazine, 1886, vol. 21, p. 385, or RUSSELL'S "Alternating Currents," vol. 1, p. 84.

$n = 6$. Then the effective inductance of 10 metres of this cable would be given by :—

$$L = 1\,000\left\{\tfrac{1}{2} + \tfrac{1}{12} + \tfrac{1}{3}\log\tfrac{2}{3} + 2\log 2\right\}$$
$$= 1\cdot 8344 \text{ microhenrys.*}$$

It has to be remembered that all the logarithms given in this paper are Napierian.

If K be the electrostatic capacity between all the small cylinders connected in parallel (Fig. 4) and the outer sheath, then by putting $d_2 = d_1 = d$ and supposing that the small cylinders are hollow, we see that when c/d and a/c are small, we have, approximately :—

$$K = \frac{n}{2\log\dfrac{d^n}{nac^{n-1}}} \quad . \quad . \quad . \quad . \quad . \quad (14)$$

A more accurate value of K got by the method of electrical images is given in Russell's "Cables and Networks," p. 294.

Similarly for the cable shown in Fig. 5 we get :—

$$K = \frac{n}{2\log\dfrac{c^{n+1}}{nad^n}} \text{ (approximately)}$$

The problems of bimetallic wires can also be readily solved by the formulæ given above. Consider two equal non-magnetic bimetallic parallel cylinders. Let c be the distance between their axes, (o, a_1) the radii of the inner metal cylinder of resistivity ρ_1, and (a_1, a_2) the radii of the outer metal cylinder of resistivity ρ_2. Then if i_1 be the current in the inner metal and i_2 be the current in the outer metal,

$$\frac{i_1}{i_2} = \frac{\rho_2 a_1^2}{\rho_1(a_2^2 - a_1^2)}$$

and if the energy be given by $\frac{1}{2}L(i_1 + i_2)^2$ we get :—

$$L = 1 + 4\log\frac{c}{a_2} + \frac{4(\rho_2 - \rho_1)^2 a_1^4}{\left\{\rho_2 a_1^2 + \rho_1(a_2^2 - a_1^2)\right\}^2}\log(a_2/a_1)$$
$$+ \frac{2\rho_1(\rho_2 - \rho_1)a_1^2(a_2^2 - a_1^2)}{\left\{\rho_2 a_1^2 + \rho_1(a_2^2 - a_1^2)\right\}^2} \quad . \quad (15)$$

Putting $\rho_2 = \rho_1$ in (14) we get the value of L for parallel cylinders each of radius a_2. Putting $\rho_2 = 0$ or $\rho_1 =$ infinity, we find that

$$L = 1 + 4\log\frac{c}{a_2} + \frac{4a_1^4}{(a_2^2 - a_1^2)^2}\log\frac{a_2}{a_1} - \frac{2a_1^2}{a_2^2 - a_1^2}$$

which gives the value of L for two parallel hollow tubes.†

We shall conclude this section by discussing the problem of a thin conducting cylindrical shell (Fig. 6) of radius d, containing two parallel cylindrical cores of radii a and b respectively. The axes of the three cylinders are supposed to lie in one plane, the axis of the shell being at an equal distance $\frac{1}{2}c$ from the other two. If we put $a = b$, we get the case of a twin concentric main. Suppose that i_1 and i_2 are the currents in the cores and that i_3 is the current in the shell. Then by the formulæ given above we find that, if $i_1 + i_2 + i_3 = 0$, the electromagnetic energy, W, is given by :—

$$W = \tfrac{1}{2}\left(\tfrac{1}{2} + 2\log\frac{d}{a}\right)i_1^2 + \tfrac{1}{2}\left(\tfrac{1}{2} + 2\log\frac{d}{b}\right)i_2^2 + 2i_1 i_2\log\frac{d}{c} \quad . \quad (16)$$

In this case

$$L_{11} = \tfrac{1}{2} + 2\log\frac{d + c/2}{a}; \quad L_{22} = \tfrac{1}{2} + 2\log\frac{d + c/2}{b}$$
$$L_{12} = L_{21} = 2\log\frac{d + c/2}{c}; \quad L_{13} = L_{23} = 2\log\frac{d + c/2}{d}$$
$$L_{31} = L_{32} = L_{33} = 0$$

It will be seen that the values of the self and inductance coefficients all depend on the value of d, except when i_3 is zero. Since i_1 and i_2 in (16) can have any values, we can deduce that the force, F, between the two cores is given by :—

$$F = \frac{\partial W}{\partial c} = -\frac{2i_1 i_2}{c} \quad . \quad . \quad . \quad . \quad (17)$$

Hence if i_1 and i_2 are flowing in the same direction so that they attract one another and c diminishes, we

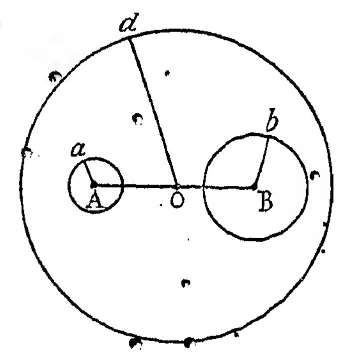

FIG. 6.

see by (17) that W increases. The work done by F in moving the wires to a smaller distance c_1 apart is equal to $2i_1 i_2\log(c/c_1)$, and this, by (16), is equal to the concurrent increase in the value of the energy W stored in the field. This is a particular case of Kelvin's theorem.

With alternating currents the mean value of F is $(2A_1A_2\cos\phi)/c$, where ϕ is the phase difference between i_1 and i_2, and A_1 and A_2 are their effective values. The force is attractive when ϕ lies between 90° and − 90°, and repulsive in other cases.

In the preceding problems we have supposed that the current is uniformly distributed over the cross-sections of the cylinders. With high-frequency currents this, however, is not the case. With very high-frequency currents, the currents are practically confined to the surfaces of the cylinders. Approximate values† for the coefficients can be found in this case.

II. THE BEST SITE FOR A POWER STATION.

In considering the best site for a power station it is helpful to know the position of the site for which

* Cf. C. E. GUYE, *Comptes Rendus*, 1894, vol. 118, p. 1329, and E. B. ROSA, *Bulletin of the Bureau of Standards*, 1907–1908, vol. 4, p. 333.
† Cf. RUSSELL'S "Alternating Currents," vol. 1, p. 88.

* RUSSELL, "Alternating Currents," vol. 1, p. 41.
† RUSSELL, *Proceedings of the Physical Society*, 1918–1919, vol. 31, p. 111.

the copper required for the feeder mains would be a minimum. In many cases the most suitable site is determined by local conditions. We have to take into account, for instance, the cost of the site, the facilities for obtaining fuel, the available supply of condensing water, whether "wayleaves" can be obtained and at what price, and many other considerations. A discussion of the simplified problem, however, leads to interesting results which are of practical value.

Formerly the only case considered was when the fractional loss of the energy was the same for every feeder. In this case it follows almost at once that the site of the power station which makes the volume of the copper used in the feeder mains a minimum, is the centre of gravity of the load. To get, however, the minimum volume of copper required for a given total power loss, it can be shown that the fractional heating loss in the feeders must be proportional to the length of the feeders.*

Let us first assume any site B and let l_n and S_n be the length and cross-section of the feeder from B to the nth distributing station A_n. Let the current taken by this station have a fixed value, I_n, and let P be the sum of the power losses in all the feeders. Then for a given value of P the requisite volume of the copper has its minimum value V, when †

$$\frac{I_1}{S_1} = \frac{I_2}{S_2} = \ldots = \frac{P}{2\rho(l_1 I_1 + l_2 I_2 + \ldots)} \quad . \quad (18)$$

where ρ is the volume resistivity of copper. It readily follows that

$$V = \frac{4\rho}{P}(l_1 I_1 + l_2 I_2 + \ldots)^2 \quad . \quad . \quad . \quad (19)$$

We see that for *any* given site the cost of the copper is reduced to a minimum when the current densities in the feeders are all equal and are given by the Equations (18). If this value of the current density be too high, then the maximum permissible value of the current density should be used. This is a useful theorem.

We now suppose that the position of the site of the power station is varied, P, I_1, I_2, etc., always having the same values. In this case we see from (19) that V depends on the square of the value of the expression $l_1 I_1 + l_2 I_2 + \ldots$ It is therefore of importance to keep this expression as small as possible. Mr. Carrothers ‡ has suggested a simple mechanical method of finding the point or points where ΣlI has a minimum value. A few general rules, however, can be given which enable this site to be found at once in special cases.

Let us first suppose that there are only two distributing centres, A_1 and A_3 (Fig. 7), and that $I_1 = I_3$. In this case $\Sigma lI = (l_1 + l_3)I_1$. Hence V has its absolute minimum value $V_{min.}$ at every point on the line A_1A_3. A considerable latitude is therefore allowed to the electrical engineer in this case. So long as the power station is not far from the line A_1A_3 the expense for the necessary copper will be near its minimum value.

* *Journal I.E.E.*, 1921, vol. 59, p. 123.
† *Ibid.*, loc. cit.
‡ *Ibid.*, 1921, vol. 59, p. 97.

Let us now suppose that $I_2 = I_4$ and that A_2A_4 intersects A_1A_3 in B. Then B is obviously the required site. The position of B is independent of the distances of A_1 and A_3 from it, so long as their loads are equal and they are on opposite sides of B. Similarly the positions of A_2 and A_4 are immaterial. It follows in the limiting case, when the lengths of BA_1 and BA_2 are zero, that B is still the most economical centre. Hence if we have three distributing stations and the load at one of them is equal to or greater than the sum of the loads at the other two, the station taking the heaviest load is the most economical site.

Similarly if there are n stations and the load at one of them equals or is greater than the sum of the loads at the others, the station taking the heaviest load gives to V its absolute minimum value $V_{min.}$.

If the power station is already erected, then, by properly choosing new distributing stations, the copper required for the mains for a given power loss in them can be made a minimum. A much greater latitude is permitted than if we were bound by the rule of choosing

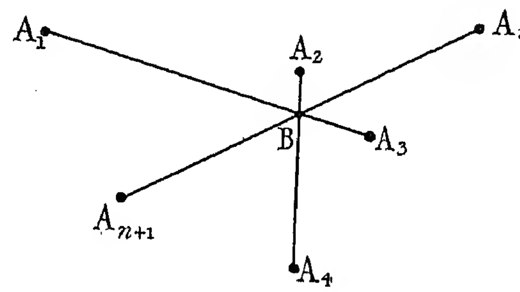

FIG. 7.

the centre of gravity of the load as the generating centre.

In any given case we first choose the site so that ΣlI is as small as practicable. We then apply Kelvin's theorem as follows. Let us suppose that the mains are loaded for H hours per annum, that the price of generating energy is q pence per kilowatt-hour, that the cost of a cubic centimetre of copper is r pence, and that interest plus depreciation is to be taken as 10 per cent. If M denote the total annual cost of the energy expended in heating the mains, together with the annual interest plus depreciation on the initial cost of the mains, we have by (19) :—

$$M = \frac{qHP}{1\,000} + \frac{r}{10} \times \frac{4\rho(l_1 I_1 + l_2 I_2 + \ldots)^2}{P}$$

If we now vary P, M has its minimum value when

$$P^2 = 400(l_1 I_1 + l_2 I_2 + \ldots)^2 \frac{\rho r}{qH}$$

Substituting this value for P in (18) we get :—

$$S_1 = \frac{I_1}{10}\left(\frac{qH\rho}{r}\right)^{\frac{1}{2}}; \quad S_2 = \frac{I_2}{10}\left(\frac{qH\rho}{r}\right)^{\frac{1}{2}} \qquad (20)$$

and the current density in all the mains is $10(r/qH\rho)^{\frac{1}{2}}$.

III. THE SPECIFICATION OF WAVE-SHAPE.

In connection with dangers from resonance, and the trouble that may be caused by interference with neighbouring telephone circuits, it is desirable to have alter-

nators which give sine-shaped waves of E.M.F. under all conditions of load. Failing this it is desirable that, at least on open circuit, they should give sine-shaped waves. We have therefore to test the purity of the wave. The physical method of doing this is to determine the amplitudes of the harmonics in the given wave by resonance methods similar to those used by Armagnat and Pupin.* I think it would be easy to standardize a method of this kind. Many manufacturers, however, think that it would be better to apply some graphical method to the oscillogram of the E.M.F. wave in order to test its departure from sine shape. In this note, therefore, the author will only discuss graphical methods.

The correct basis to determine whether a given wave approximates with sufficient accuracy to sine shape or not is to know whether the ratios of the amplitudes of the third and higher harmonics to the amplitude of the first harmonic are less than certain specified fractions. In many cases one or two simple measurements will serve to reject the wave. As some of the methods in use seem unsuitable it will be helpful to give a brief *résumé* of them and suggest more promising methods. Alternating waves only will be considered, that is, waves for which

$$y = f(x) = -f(x + \lambda/2) = f(x + \lambda)$$

where λ is the wave-length of the complete alternating-current wave. It can be shown that

$$y = a_1 \cos \frac{2\pi}{\lambda}x + a_3 \cos 3\frac{2\pi}{\lambda}x + \dots$$
$$+ b_1 \sin \frac{2\pi}{\lambda}x + b_3 \sin 3\frac{2\pi}{\lambda}x + \dots \quad (21)$$

The amplitude of the $(2n+1)$th harmonic is $(a_{2n+1}^2 + b_{2n+1}^2)^{\frac{1}{2}}$ and its phase lag [see (26)] is given by $\tan \alpha_{2n+1} = a_{2n+1}/b_{2n+1}$. In (21) the standard practice is to write the coefficients a for the cosine terms and the coefficients b for the sine terms.

During the past 100 years several mathematicians have suggested that if we neglect all terms of order greater than $2n+1$ in (21) and take the values of y corresponding to $2n$ different values of x, we get $2n$ equations from which the $2n$ constants $a_1, a_3 \dots a_{2n+1}$ and $b_1, b_3, \dots b_{2n+1}$ can be found. Obviously for high values of n the method is laborious, but several ingenious schedules have been devised which reduce the labour to a minimum.

It is evident that we can only be sure that the results found in this way are correct when the harmonics higher than the $(2n+1)$th are not present in the wave. What is done is to find the curve of the form (21), where a_{2n+1} and b_{2n+1} are the highest terms on the right-hand side, which passes through the extremities of the ordinates $y_1, y_2 \dots y_{2n}$, and then assume that the values of $a_1, a_2 \dots b_1, b_2 \dots$ give the required Fourier coefficients. Gauss† showed that this method can be used for interpolation, and applied it to astronomical problems. It may be useful for this purpose, but for the practical determination of the harmonics it is not suitable as it is laborious and theoretically inaccurate.

* RUSSELL, "Alternating Currents," vol. 2, chap. iv.
† C. F. GAUSS, "Werke," band 3, p. 265.

The method the author adopts is to take the Fourier solutions for a_n and b_n which are given in the form of integrals, and use methods of evaluating them which are well known to mathematicians and actuaries.

Fourier showed that

$$a_n = \frac{2}{\lambda}\int_0^\lambda f(x) \cos n\left(\frac{2\pi x}{\lambda}\right)\partial x \quad (22)$$

and

$$b_n = \frac{2}{\lambda}\int_0^\lambda f(x) \sin n\left(\frac{2\pi x}{\lambda}\right)\partial x \quad (23)$$

Now since $\int_0^\lambda y\partial x$ is simply the area enclosed between a curve and the axis of x, we see that a_n and b_n are equal to the areas enclosed by the curves,

$$y = f(x) \cos n\left(\frac{2\pi x}{\lambda}\right) \quad \dots \dots \quad (24)$$

and

$$y = f(x) \sin n\left(\frac{2\pi x}{\lambda}\right) \quad \dots \dots \quad (25)$$

from 0 to λ multiplied by $2/\lambda$.

The problem is therefore reduced to that of finding the area enclosed by a curve. If we use the planimeter,

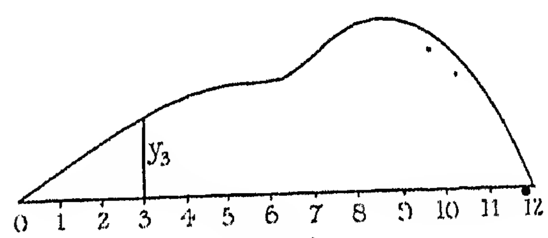

FIG. 8.

however, it would be necessary to draw the graphs of (24) and (25), and this would be laborious. We therefore use the methods of graphical quadrature and draw ordinates.* By drawing a sufficient number of ordinates we can find, theoretically at least, the values of a_n and b_n to any required degree of accuracy.

In practice the accurate measurement of the lengths of 11 ordinates of the given wave is about all that we could reasonably demand from an engineer. We suppose that the base of the positive half of the wave (Fig. 8) is divided into 12 equal parts and that ordinates $y_0, y_1, y_2, \dots y_{12}$ are erected at the extremities of these parts. In practice $y_0 = y_{12} = 0$.

With eleven ordinates we can calculate with sufficient accuracy the value of the first harmonic, the third harmonic and the effective, or root-mean-square, value of the wave by means of the formulæ given below. These values are often sufficient to enable us to judge the wave. In alternating-current notation we suppose that the wave is given by

$$e = E_1 \sin(\omega t - \alpha_1) + E_3 \sin(3\omega t - \alpha_3) + \dots \quad (26)$$

* RUSSELL, "Alternating Currents," vol. 2, p. 132.

Then simplifying the formulæ given in Russell's "Alternating Currents" (vol. 2, p. 132) we get:—

$$E_1 \sin \alpha_1 = \tfrac{1}{40}\{2(y_0 - y_{12}) + y_4 - y_8\} + \frac{\sqrt{3}}{40}(y_2 - y_{10}) + \frac{3\sqrt{2}}{20}(y_3 - y_9) + 0{\cdot}241(y_1 - y_{11}) + 0{\cdot}065(y_5 - y_7) \quad . \quad . \quad . \quad . \quad . \quad (27)$$

and

$$E_1 \cos \alpha_1 = \tfrac{1}{40}(y_2 + 4y_6 + y_{10}) + \frac{\sqrt{3}}{40}(y_4 + y_8) + \frac{3\sqrt{2}}{20}(y_3 + y_9) + 0{\cdot}241(y_5 + y_7) + 0{\cdot}065(y_1 + y_{11}) \quad . \quad . \quad . \quad . \quad . \quad (28)$$

Squaring and adding the values of $E_1 \sin \alpha_1$ and $E_1 \cos \alpha_1$ given by these equations, we find E_1^2 and thus we can find E_1.

Similarly, we have:—

$$E_3 \sin \alpha_3 = \tfrac{1}{20}(y_0 - y_4 + y_8 - y_{12}) + \frac{\sqrt{2}}{8}(y_1 + y_7 - y_5 - y_{11}) + \frac{3\sqrt{2}}{20}(y_9 - y_3) \quad . \quad (29)$$

and

$$E_3 \cos \alpha_3 = \tfrac{1}{20}(y_2 + y_{10} - 2y_6) + \frac{\sqrt{2}}{8}(y_1 + y_{11} - y_5 - y_7) + \frac{3\sqrt{2}}{20}(y_3 + y_9) \quad . \quad (30)$$

Hence E_3 is easily determined from these two equations. If V be the effective value of e, we get by a double application of Weddle's rule for finding areas:—

$$V^2 = \tfrac{1}{40}\{y_0^2 + y_2^2 + y_4^2 + 2y_6^2 + y_8^2 + y_{10}^2 + y_{12}^2\} + \tfrac{1}{8}(y_1^2 + y_5^2 + y_7^2 + y_{11}^2) + \tfrac{3}{20}(y_3^2 + y_9^2) \quad . \quad . \quad (31)$$

Table 1 has been computed by means of (28), (30) and (31). All the waves being symmetrical, α_1 and α_3 are zero.

TABLE 1.

Shape	$y_{max.}$	V	E_1	E_3
Rectangular ..	1	1	1·273	0·424
Circular	1	0·816	1·134	0·188
Parabolic	1	0·730	1·032	0·038
Sine	1	0·707	1·000	0·000
*Circular topped ..	1	0·707	0·999	−0·013
Triangular ..	1	0·577	0·811	−0·090

As we always have

$$2V^2 = E_1^2 + E_3^2 + E_5^2 + \ldots \quad . \quad . \quad . \quad . \quad (32)$$

this suggests that the harmonic factor † which equals

$$\frac{\{2V^2 - E_1^2\}^{\frac{1}{2}}}{E_1} \quad \text{or} \quad \frac{\{E_3^2 + E_5^2 + \ldots\}^{\frac{1}{2}}}{E_1}$$

might be taken as a criterion for sine shape. From the table given above we see that for a rectangular wave the harmonic factor is 0·48; for a circular wave 0·19; for a parabolic wave 0·04; and for a triangular wave 0·12. Unfortunately, for waves which are very approximately sine-shaped, V and E_1 have to be determined with an accuracy much exceeding the probable accuracy of the measurements of the ordinates in order to get an accurate value for the harmonic factor. It is therefore of little use for the end we have in view.

Another factor that is often used is the "deviation factor." This factor * is defined as follows: "The deviation factor of a wave is the ratio of the maximum difference between corresponding ordinates of the wave and of the equivalent sine wave of equal length to the maximum ordinate of the equivalent sine wave when the waves are superposed in such a way as to make this maximum difference as small as possible."

To examine this definition, let us consider those waves for which e has a large maximum value when ωt in (26) is 90° and for which $\alpha_1 = \alpha_3 = \ldots = 0$.

In this case the deviation factor is

$$\frac{(E_1^2 + E_3^2 + \ldots)^{\frac{1}{2}} - E_1 + E_3 - E_5 + \ldots}{(E_1^2 + E_3^2 + \ldots)^{\frac{1}{2}}}$$

This fraction is a complicated function of the amplitudes of the harmonics, and there is no mathematical reason why we should adopt it. By considering special cases also it can be shown that the value of the deviation factor varies with the time-lags of the various harmonics. There seems to be no justification for using such a definition.

As formula (31) is new some may hesitate to accept it. As we have so many ordinates, however, the ordinary formulæ for V^2, namely,

$$12V^2 = \frac{y_0^2 + y_{12}^2}{2} + y_1^2 + y_2^2 + \ldots + y_{11}^2 \quad . \quad (A)$$

or better, $\quad 12V^2 = Y_1^2 + Y_2^2 + \ldots + Y_{12}^2 \quad . \quad . \quad . \quad (B)$

where Y_1, Y_2, are the ordinates at the midpoints of the portions into which the base is divided, may be used. Table 2 shows the errors introduced by these formulæ when applied to find V^2.

TABLE 2.

Shape	Error using (A)	Error using (B)
	Per cent	Per cent
Rectangular	Correct	Correct
Circular	0·7 high	0·3 low
Parabolic	0·005 low	0·004 high
Sine	Correct	Correct
Circular topped	Correct	Correct
Triangular	1·4 high	0·7 low

It is curious to notice that if we divide the base of a sine wave into n equal parts and use formulæ similar to (A) and (B) we always get the correct answer in both cases. The result given by formula (31) gives the exact answer in all the cases considered above.

* The top part of this curve is the quadrant of a circle of radius unity. The tangents at the ends of the quadrant form the rest of the wave. They are inclined to the axis at an angle of 45°.

† BEDELL, *Transactions of the American Institute of Electrical Engineers*, 1915, vol. 34, p. 1135.

* Standards of the American Institute of Electrical Engineers, Def. 3274, 1921.

It is not difficult to find a case where using (31) would introduce an error. Take, for example, a symmetrical trapezoidal wave the top part of which is a line parallel to the base and equal to one-third of it. If the maximum height of the wave is unity, we have :—

by (A), $V^2 = \frac{5}{9}(1 + \frac{1}{80})$.
by (B), $V^2 = \frac{5}{9}(1 - \frac{1}{160})$
and by (31), $V^2 = \frac{5}{9}(1 - \frac{1}{64})$

The true value of V^2 is $\frac{5}{9}$, so in this case (31) actually gives the greatest error, V determined in this way being nearly $0 \cdot 8$ of one per cent too small. The reason of this is that there are two points of mathematical discontinuity in the wave, and (31) has been obtained on the assumptions that *smooth* curves have been drawn through the extremities of the ordinates y_0, $y_1, \ldots y_6$ and through $y_6, y_7, \ldots y_{12}$. As points of discontinuity do not occur on practical waves, (31) is the safest formula to use. By the use of similar formulæ actuaries check "tables of mortality" which are obviously governed by no simple law. A serious objection to using (B) is that it entails the labour of measuring the lengths of the 12 new ordinates Y_1, Y_2, $\ldots Y_{12}$.

Four additional formulæ,* which are useful when judging wave shape, can be written down at once from (26). We get

$$E_1 \sin a_1 + E_3 \sin a_3 + E_5 \sin a_5 + \ldots = y_0 \quad . \quad (33)$$

$$E_1 \cos a_1 - E_3 \cos a_3 + E_5 \cos a_5 - \ldots = y_6 \quad . \quad (34)$$

$$E_3 \sin a_3 + E_9 \sin a_9 + E_{15} \sin a_{15} + \ldots = \tfrac{1}{3}(y_0 - y_4 + y_8) \quad . \quad (35)$$

$$E_3 \cos a_3 - E_9 \cos a_9 + E_{15} \cos a_{15} - \ldots = \tfrac{1}{3}(y_2 - y_6 + y_{10}) \quad . \quad (36)$$

No new measurements have to be made as we are using the same ordinates as those we used for determining $E_1 \sin a_1$, $E_1 \cos a_1$, $E_3 \sin a_3$ and $E_3 \cos a_3$. If $y_0 - E_1 \sin a_1$ is not very small compared with E_1, then by (33) some of the higher harmonics are appreciable and the wave could be rejected. Similarly by (34) $y_6 - E_1 \cos a_1$ must be very small compared with E_1. Two other similar conditions are got from (35) and (36). If any of these four conditions is not satisfied the wave can be rejected. It does not necessarily follow that if they are satisfied the wave is approximately sine-shaped. But if $\sqrt{2}V - E_1$ is equal to zero within the limits of errors of measurement, if also E_3/E_1 is a very small fraction and the four conditions stated above are satisfied, the curve might be accepted, provided there were no obvious ripples on it.

If there is a ripple on the wave the frequency of which shows that it is a harmonic of frequency m, its amplitude could be accurately determined by the following equations :—

$$E_m \sin a_m = \frac{1}{2m}\left\{ y_0 - y_{\frac{\lambda}{2m}} + y_{\frac{2\lambda}{2m}} - \ldots - y_{\frac{(2m-1)\lambda}{2m}} \right\} \quad . \quad (37)$$

$$E_m \cos a_m = \frac{1}{2m}\left\{ y_{\frac{\lambda}{4m}} - y_{\frac{3\lambda}{4m}} + y_{\frac{5\lambda}{4m}} - \ldots - y_{\frac{(4m-1)\lambda}{4m}} \right\} \quad . \quad (38)$$

where λ is the wave-length of the complete alternating wave.

As an example, consider a rectangular wave of height unity. In this case $\sqrt{2}V - E_1 = 0 \cdot 141$ and $E_3/E_1 = 0 \cdot 333$. Neither of the first two conditions would be admissible. Formulæ (33) and (35) are satisfied, but (34) and (36) give $-0 \cdot 273$ and $-0 \cdot 091$, neither of which would be admissible.

As another example consider a semi-circular wave of height unity. In this case $\sqrt{2}V - E_1 = 0 \cdot 021$, $E_3/E_1 = 0 \cdot 166$ and (34) and (36) give $-0 \cdot 134$ and $0 \cdot 070$. Remembering that E_1 is $1 \cdot 134$ we see that any of these four would reject the wave.

This section may be summed up as follows. Neither the harmonic factor nor the deviation factor is of much use in determining whether a wave is approximately sine-shaped or not. At present it does not seem feasible to measure graphically with sufficient accuracy the high harmonics of a wave. We can, however, measure without much labour the values of the amplitudes of the first and third harmonics, and the effective value of the wave, with sufficient accuracy for practical purposes by only measuring eleven ordinates. From these values we deduce critical formulæ which enable us to rule out certain waves. Visual comparison of the so-called equivalent sine wave with the wave being inspected might be used. But unless the two curves are practically coincident the methods described above are preferable. A method of finding the accurate value of the amplitude of a harmonic ripple on the wave is given.

If this graphical method or an improved graphical method on similar lines be not acceptable, we shall have to fall back on experimental methods of finding the amplitudes of the harmonics. The wave can only be judged when we know its harmonics or superior limits to their values or to the sum of their values.

IV. The Power and Balance Factor of a Polyphase Load.

The author has previously discussed * whether it is possible to define the power factor of a polyphase load in such a way that a knowledge of its value will be of assistance to an engineer in judging the desirability or otherwise of a given unbalanced load. It was proved that if the power factor were defined in a certain way and if, in addition, a quantity called the "balance factor" were defined, then a knowledge of their values would be a help to the engineer. It will be useful, therefore, to give these definitions and to give also a *résumé* of the theorems on which they are founded.

Let us first consider a three-phase case where the voltages between the lines are all equal and their phase

* Cf. Silvanus Thompson, *Proceedings of the Physical Society*, 1910–1911, vol. 23, p. 334, or Russell's "Alternating Currents," vol. 2, p. 128.

* *Faraday House Journal*, 1922, vol. 9, p. 73. See also the many instructive papers on polyphase power factor which were read at the Annual Convention of the American Institute of Electrical Engineers held at White Sulphur Springs on June 29, 1920.

differences, consequently are also equal. If w denote the instantaneous value of the power supplied to the load, we have, with the usual notation:—

$$w = e_1 i_1 + e_2 i_2 + e_3 i_3$$

Assuming that $e_1 = E \sin \omega t$, $e_2 = E \sin (\omega t - 120^\circ)$ and $e_3 = E \sin (\omega t - 240^\circ)$, and writing V for the effective value of e, and A_1, A_2 and A_3 for the effective values of i_1, i_2 and i_3 respectively, we get, if ϕ_1 denote the phase difference between e_1 and i_1:—

$$\begin{aligned} w = {} & VA_1 \{ \cos \phi_1 - \cos (2\omega t - \phi_1) \} \\ & + VA_2 \{ \cos \phi_2 - \cos (2\omega t - \phi_2 - 240^\circ) \} \\ & + VA_3 \{ \cos \phi_3 - \cos (2\omega t - \phi_3 - 120^\circ) \} \\ = {} & R \cos \phi - Q' \cos (2\omega t - \gamma) \quad . \quad . \quad . \quad . \quad . \quad . \quad (39) \end{aligned}$$

where

$$R \cos \phi = VA_1 \cos \phi_1 + VA_2 \cos \phi_2 + VA_3 \cos \phi_3 \quad (40)$$

$$Q'^2 = V^2[\Sigma A_1^2 + 2\Sigma A_1 A_2 \cos \{\phi_1 - \phi_2 + 120^\circ\}]$$

and $\tan \gamma$

$$= \frac{A_1 \sin \phi_1 + A_2 \sin (\phi_2 + 240^\circ) + A_3 \sin (\phi_3 + 120^\circ)}{A_1 \cos \phi_1 + A_2 \cos (\phi_2 + 240^\circ) + A_3 \cos (\phi_3 + 120^\circ)}$$

Since $i_1 + i_2 + i_3 = 0$, we easily deduce that

$$0 = \Sigma A_1^2 + 2\Sigma A_1 A_2 \cos (\phi_1 - \phi_2 - 120^\circ)$$

Hence

$$Q'^2 = 2V^2 \{ \Sigma A_1^2 - \Sigma A_1 A_2 \cos (\phi_1 - \phi_2) \} \quad (41)$$

The quantity Q' is measured in volt-amperes and gives the amplitude of the double frequency component of the instantaneous power. We see from (41) that it does not vanish when $\phi_1 = \phi_2 = \phi_3 = \phi$ unless we have also $A_1 = A_2 = A_3$.

This shows that to specify a given load usefully we must know not only how the phase differences are balanced but also how the currents are balanced. The first term on the right-hand side of (39) gives the average total power taken by the consumer. From analogy with the single-phase case we have denoted this by $R \cos \phi$. R has the dimensions of volt-amperes but we have not yet defined R and ϕ.

In order to fix our ideas and see the nature of the problem more clearly we shall have recourse to geometry. We shall make the theorems more general by removing the restrictions about the amplitudes and shapes of the E.M.F. waves. To simplify them, however, we shall only consider the three-phase case.

By means of three ordinary wattmeters we can read the power taken at the terminals 1, 2 and 3. Let the readings be $V_1 A_1 \cos \phi_1$, $V_2 A_2 \cos \phi_2$ and $V_3 A_3 \cos \phi_3$ respectively. From analogy with (40) we write:—

$$R \cos \phi = \Sigma V_1 A_1 \cos \phi_1 \quad . \quad . \quad . \quad . \quad (42)$$

Similarly by a meter for the wattless current we find $V_1 A_1 \sin \phi_1$, $V_2 A_2 \sin \phi_2$ and $V_3 A_3 \sin \phi_3$. It has to be remembered that any of the meters may run backwards. If the wattmeter connected with the first main run backwards then ϕ_1 must be greater than $\frac{1}{2}\pi$ or less than $-\frac{1}{2}\pi$.

We now fix the values of R and ϕ by assuming that they are connected by the additional equation

$$R \sin \phi = \Sigma V_1 A_1 \sin \phi_1 \quad . \quad . \quad . \quad . \quad (43)$$

Equations (42) and (43) show that if we draw forces $V_1 A_1$, $V_2 A_2$ and $V_3 A_3$ inclined to the axis of x at angles ϕ_1, ϕ_2 and ϕ_3, then R gives the magnitude of their resultant and makes an angle ϕ with the axis.

In Fig. 9, let $OQ_1 = V_1 A_1$, $OQ_2 = V_2 A_2$ and $OQ_3 = V_3 A_3$. Let also the angles Q_1OX, Q_2OX and Q_3OX equal ϕ_1, ϕ_2 and ϕ_3 respectively. This diagram pictures the volt-amperes taken by the consumer and the phase angles at which they are taken, but otherwise it has no physical signification. The quantity R is the resultant of OQ_1, OQ_2 and OQ_3. If G be the centre of gravity of the triangle $Q_1Q_2Q_3$, by a well-known theorem in statics, $R = 3 \cdot OG$, and the angle GOX equals ϕ. R and ϕ are therefore the same wherever Q_1, Q_2 and Q_3 are, provided that the centre of gravity of the triangle formed by them is at G. Of the loads that have the same R and ϕ, some are obviously more desirable

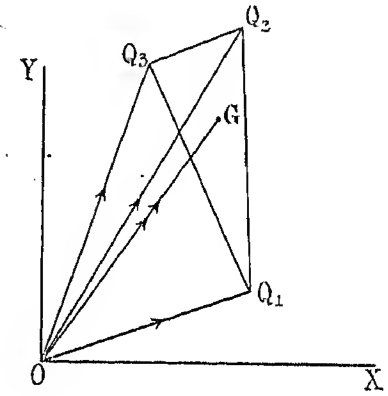

FIG. 9.

from the supply point of view than others. A knowledge of R and ϕ gives us no information about the lack of balance of the currents. We have therefore to find an expression which measures in some way the want of balance of the volt-amperes.

Let $OQ_1 = R_1$, $OQ_2 = R_2$ and $OQ_3 = R_3$ (Fig. 9). By algebra we have

$$3(R_1^2 + R_2^2 + R_3^2) = (R_1 + R_2 + R_3)^2 + (R_1 - R_2)^2 + (R_2 - R_3)^2 + (R_3 - R_1)^2$$

Hence we see that, for a given aggregate value of the volt-amperes, $R_1 + R_2 + R_3$, $\sqrt{3}(R_1^2 + R_2^2 + R_3^2)^{\frac{1}{2}}$ has its minimum value, $R_1 + R_2 + R_3$, when $R_1 = R_2 = R_3$, i.e. when the volt-amperes are balanced. From Fig. 9 we see that when $R_1 + R_2 + R_3$ is fixed, R has its maximum value $R_1 + R_2 + R_3$ when $\phi_1 = \phi_2 = \phi_3$. Hence for a given aggregate value of the volt-amperes, R is less than $\sqrt{3}(R_1^2 + R_2^2 + R_3^2)^{\frac{1}{2}}$, except when both $R_1 = R_2 = R_3$ and $\phi_1 = \phi_2 = \phi_3$. This suggests the following definition of the balance factor, b:—

$$b^2 = \frac{R^2}{3(R_1^2 + R_2^2 + R_3^2)} \quad . \quad . \quad . \quad . \quad (44)$$

It will be seen that the greater the value of b the better the balance of the load, and that when b is unity the load is perfectly balanced.

It may be objected that (44) is a purely artificial definition. That it has some physical as well as geometrical significance will appear if we introduce the definition of the lack of balance, or "unbalance" factor u of the load. We define this quantity by the equation

$$u^2 = \frac{Q^2}{3(R_1^2 + R_2^2 + R_3^2)} \quad . \quad . \quad . \quad . \quad (45)$$

where $Q^2 = Q_1Q_2^2 + Q_2Q_3^2 + Q_3Q_1^2 =$ the sum of the squares of the sides of the triangle $Q_1Q_2Q_3$ (Fig. 9). The value of u is zero when the load is balanced, and it has its maximum value of unity when R is zero and G coincides with O.

By considering the moments of inertia of three equal particles placed at Q_1, Q_2 and Q_3 respectively (Fig. 9) about axes at O and G perpendicular to the plane of the paper, we get at once that

$$R_1^2 + R_2^2 + R_3^2 = 3 \,.\, OG^2 + GQ_1^2 + GQ_2^2 + GQ_3^2$$

Hence

$$3(R_1^2 + R_2^2 + R_3^2) = R^2 + 3(GQ_1^2 + GQ_2^2 + GQ_3^2)$$
$$= R^2 + Q^2 \quad . \quad (46)$$

It follows that $\qquad b^2 + u^2 = 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$

It is to be noticed on our assumptions that Q_1Q_2 is the vector difference between R_1 and R_2, Q_2Q_3 is the vector difference between R_2 and R_3, and Q_3Q_1 is the vector difference between R_3 and R_1. Hence Q is the vector sum of these unbalanced volt-amperes supposed to act at right angles to one another.

If we rotate the triangle $Q_1Q_2Q_3$ (Fig. 9) about its centre of gravity, G, we get different simultaneous values of R_1, R_2 and R_3, all of which have the same R, Q, ϕ, b and u as the original load. Every triangle $Q_1Q_2Q_3$, the sum of the squares of the sides of which is Q^2 and the centre of gravity of which is at G, will give values to R_1, R_2, R_3, ϕ_1, ϕ_2 and ϕ_3 which will give the same values to R, u and ϕ, or to R, b and ϕ. None of the members of the group of loads which are specified by R, b and ϕ seems to be appreciably more or less attractive to the supply engineer than the others. We therefore suggest that for a rough specification of the magnitude and character of a given load it is sufficient to specify values for R, b and ϕ respectively.

We see that R is the value of the aggregate volt-amperes when $\phi_1 = \phi_2 = \phi_3 = \phi$. It may therefore be called the "equal phase volt-amperes" of the given load.

From Fig. 9 we see that

$$Q^2 = Q_1Q_2^2 + Q_2Q_3^2 + Q_3Q_1^2$$

and when $V_1 = V_2 = V_3 = V$, we get

$$Q^2 = 2V^2[\Sigma A_1^2 - \Sigma A_1A_2 \cos(\phi_1 - \phi_2)]$$
$$= Q'^2$$

Thus for sine waves and balanced voltages

$$w = R\cos\phi - Q\cos(2\omega t - \gamma) \quad . \quad . \quad (48)$$

Q in this case has a definite physical meaning. It is the amplitude of the double frequency component of the instantaneous value of the power. Hence b and u have physical meanings. In general, R and Q are connected with the volt-amperes by the simple relation (46).

It may be asked why do we not take Q/R as the measure of the unbalance of the load. The objection to this is that Q/R can have any value between zero and infinity. In my opinion it is better to use a balance or an unbalance factor which cannot be greater than unity.

Let us now consider how the quantities R, b and ϕ can be measured. We can easily measure the power and the wattless volt-amperes taken at the three feeding points, by means of a wattmeter and a meter for the wattless volt-amperes. Denoting these readings by $R_1\cos\phi_1$, $R_2\cos\phi_2$, $R_3\cos\phi_3$, $R_1\sin\phi_1$, $R_2\sin\phi_2$ and $R_3\sin\phi_3$ respectively, we get:—

$$R\cos\phi = R_1\cos\phi_1 + R_2\cos\phi_2 + R_3\cos\phi_3 = a$$
and $$R\sin\phi = R_1\sin\phi_1 + R_2\sin\phi_2 + R_3\sin\phi_3 = b$$

Thus $R = (a^2 + b^2)^{\frac{1}{2}}$ and $\tan\phi = b/a$. We determine $\tan\phi_1$ and therefore ϕ_1 by dividing the reading of the wattless meter by the reading of the wattmeter. Hence we find $\cos\phi_1$ and, dividing the reading of the wattmeter by $\cos\phi_1$, we get R_1. Similarly we get R_2 and R_3. We then find b easily by (44).

This procedure seems lengthy at first sight, but it must be remembered that a three-phase consumer can take a given amount of power in an infinite variety of ways, some of which would be very objectionable to the supply engineer. Doubtless simpler methods of determining P, b and ϕ will be discovered. Instruments also may be devised for determining these quantities at once.

WESTERN CENTRE: CHAIRMAN'S ADDRESS

By C. T. Allan, Member.

(Abstract *of Address delivered at* Cardiff, 15*th October*, 1923.)

I wish to deal to-night with a subject that has been in my mind for a long time past, namely, the training and, more particularly, the status of the engineer, especially the electrical engineer.

First of all a few words about the training of young engineers—the youths whose capabilities will in the near future determine the position which Great Britain is to occupy among the engineering nations of the world.

I sometimes ask myself if we are not too intent upon producing craftsmen—skilled manual workers—and too often forgetful of the demand for thinkers, men of brains with creative ideas and higher technical knowledge. The latter species must always be rarer than the man with clever fingers; but that is all the more reason for seeking him out and cultivating him.

Take two average young men who desire to be engineers and whose fathers, with average family expenses, can only afford to pay for two or three years' training.

Assume that one of the young men apprentices himself, is taught craftsmanship, and attends evening classes (if he is near them). At the end of his training he is at best an average craftsman or draughtsman—if indeed he has not been left in a groove as a turner or a fitter, or specialized in some particular work for which his foreman thought he showed an aptitude.

Assume that the other young man takes a course at a technical college and takes his diploma or degree after he has been trained to use his brain. His hands will probably have been fairly well trained in the college workshops and during the vacation courses at the neighbouring works.

Both young fellows then begin seeking further advancement. After many vicissitudes they will advance, but when they reach the age of thirty, one of them will be holding a more important job than the other; I am sure that that one will be the one with the trained brain. He will more quickly be able to grasp and solve problems. He will understand more intelligently the meaning and use of the practical appliances that surround him. Both men at the start may have to take jobs as labourers to keep themselves alive, but I know which one will take most advantage of every step that leads to the top. They may neither of them continue to earn their living as engineers, but still the acceleration of the man with the trained brain will be the faster. I am not speaking of freaks, or what I term "brains on legs," but of average level-headed men.

I think that the fetish of manual training is often overdone, because the present-day machine and mass-production methods may often leave an apprentice with little knowledge beyond that of operating one or two machines. I am not decrying manual training in reason, but I remember that the late war showed that an intensive course quickly made raw material into specialized craftsmen. I expect that some of you saw lawyers working lathes, women welding joints, insurance agents as colliers, and publicans firing boilers, as though to the manner born. (Moreover, a civil engineer does not take any part of his training at a bench, and a marine engineer to obtain his certificate must, in addition to his practical work, also have his brain trained.)

Some of the Continental nations do not allow an engineer to practise until he has taken his degree, and it is from these nations that we have to expect fiercer and still fiercer competition in the coming commercial war. We must be prepared to go one better and make an even better product than they to keep our place at the head. Did not the engineers' war, as it was termed, prove that after the men of the British Empire got into their stride they were supreme on the sea and under it, on the land and over it?

When the coming commercial war arrives we must be already in our stride, by preparing the brains of those who are to succeed the young fellows who gave their lives for their country. I believe that this advanced training should be within the reach of all, even free of cost if possible, and the money spent for such a purpose would be returned a hundredfold, nay a thousandfold.

Doctors cannot practice until they have taken their degree; the same is true of clergymen; marine engineers must have a certificate. The trained mind and the trained mind alone can enter into the professions and the higher branches of business.

Our own Institution is leading the way to the production of a technical engineer by its Associate Membership Examination. This is a step in the right direction, but much remains to be done. It has too long been an accepted belief that the technical man can have no proper grasp of business methods and finance. We might be poets and dreamers for all the faith that is displayed by some people in our knowledge of economics. And so we see big undertakings which are essentially engineering concerns under the charge of actuaries, accountants and other specialists in "business methods." On engineering matters these people may be even more ignorant than we are of the niceties of advanced accounting, and they must rely on the advice of their technical staff.

Still, it is undeniable that money talks—and so our young men must have sound training on the management of that eloquent commodity. So far as I can find, none of the technical colleges teaches the art of

economically spending money. Yet an engineer has been described as a man who knows how to do a job for one pound that anyone else could not do for two. Why not encourage him to learn how to do it for ten shillings, by discovering as a student what an invoice is, what happens after he has made out a requisition, what a cost-sheet looks like and what it is for, what accounts for the margin between profit (success) and loss (failure) ?

If the commercial side were added to the training of an engineer, then we might see engineers at the head of more of our industries. In my own company our engineer trainees, by the willing co-operation of the accountants' department, obtain an intensive training in the costing, invoicing, wages and purchasing sections. I heard of two Canadian power company engineers who were looking for a taxi to take them on an inspection. One taxi driver offered his services for considerably less than the other drivers; when asked how he could underbid the others, he said: "I am now a shareholder in your company and am interested in its success. I am making only a little more than my expenses on this trip, but it will come back to me in dividend." Needless to say this taxi driver is getting all the business that the power company can give him. My point is, that if the taxi driver understands what costs and dividends mean, even more so should a young engineer know.

At that I must for the time being leave this question of training, but I sincerely hope that the members of our Institution will give earnest consideration to the points I have raised—the necessity of making the majority of recruits to our profession trained thinkers and brain-workers; and the equally urgent necessity of extending the scope of their technical education so that they may acquire that knowledge of business methods and that capacity for organization which are necessary in the higher appointments. To the young engineer I therefore say: Have confidence, for—

"If you think you're outclassed you are,
You've got to think high to rise,
You've got to be sure of yourself before
You ever can win a prize.
Life's battles don't always go
To the stronger or faster man
But soon or late the man who wins
Is the fellow who thinks he can."

Now let us for a few minutes examine the present status of the already qualified engineer. Why is it that the engineering Institutions have had such an uphill job in establishing the status of the engineer ? Why is he so little understood and appreciated ? Why are his works made ridiculous by a blundering general Press ? Why do non-engineer officials try to thrust him into a back seat ? Why is it we so seldom find his name on his masterpieces ?

The artist takes care to sign his pictures, the eminent actor insists that his name shall appear in large type on the play-bills; even the clerk to the parish council has his name emblazoned on a public notice board, but the engineer's name is seldom to be found.

Members have doubtless seen on the commemoration stones of large public works or buildings the names of the mayor, the aldermen, the councillors, the clerk to the council and perhaps—perhaps, I say—in a corner at the bottom and in small letters the name of the engineer who really did the job.

Upon a prospectus of an engineering venture we find the names of the directors and their titles in full, the stockbroker, the secretary, the solicitor, but seldom or never the name of the man who is going to build the concern and make it run—the engineer. If it does appear he is accused of advertising.

That brings me at once to the bed-rock of the whole question—publicity. Let us dismiss from our minds at once any suspicion that I am asking engineers to advertise in newspapers or handbills. The Institution to which we belong has laid down very proper rules as to professional conduct, and we gladly uphold those rules. Yet the present position is very unsatisfactory; the engineer is isolated.

The doctor comes into frequent contact with all his patients; the actor appears before big audiences; the artist, novelist and dramatist are interviewed and newspapers make them famous.

The minister of religion preaches to whole congregations, and the people know his voice and manner. Even the great soldier, the great sailor, the great lawyer are known to large bodies of men.

The engineer, usually serving boards of directors and corporations without body or soul, is known only to his own staff; beyond them he is a mystery. He might be a hermit for all the public know.

On the films we see the airman, the musician, the traveller, the soldier, the artist, the actor, the sculptor, kings, queens, bishops, Members of Parliament. But did we ever see an engineer on the films ? What is he like ? How would we know him ? Would he be armed with sword or a soldering iron ?

Some may think that this does not matter; but I believe that it matters very much. For better or for worse, the age of publicity has dawned. The rewards of modern life are in proportion to merit and publicity judiciously mingled. Make no mistake, however, pure unadulterated merit has only a dog's life to expect. Unfortunately, publicity can do almost anything. We may put up pure chalk as a tooth powder, and all that we have to do is to spend enough on publicity and it will go like wildfire.

I believe that electrical engineers have the best commodity in the world to sell, and that hitherto we have not known how to sell it. Sometimes the engineer affects to despise publicity, maintaining that it is not of his world. To him it matters not a jot. His duty is to his employers; to laymen he has nothing whatever to say. He is wrong; he is utterly wrong, and the British engineer in particular is wrong. Not only has he personally suffered from his own isolation; the progress of engineering in general has suffered because we are uncommunicative.

In Chicago there is a demand of no less than 800 kWh per annum for every man, woman and child. The average in this country—80—is considered to be quite a respectable figure. Why this astonishing contrast ?

Some of it may be due to cheap English gas. Some of it is due to the American consumer being more willing to try a new thing; but when all is said and done, quite a lot of the difference is due to the fact that the American electric supply interests understand publicity and that ours do not.

We are now being taught and we all admire the good work of the British Electrical Development Association, who are, however, working under a handicap, namely, lack of funds. They should be in a position to spend £10 where at present they spend only £1. This would enable them to influence public opinion a great deal more, whereas on their present meagre basis they must largely content themselves with internal work amongst the electrical industry itself.

I have given the above instance of the greater use of electricity in America, which is also true as regards Switzerland, Italy, Sweden and many European countries, because I maintain that the British engineer is altogether lacking in the spirit of commercial publicity, both with regard to his inventions and with regard to himself.

The engineer undoubtedly is the head of the modern community. The people are transported by him, lighted, warmed, fed, given their news, their entertainment, their clothes, their telegrams, their national defence, their fuel, water, furniture, buildings and sanitation—all due to the engineer. But although all this is due to him, although he does more for the civilized community than any other profession, he is as isolated and unknown as though he lived on a desert island. He is so obscure that writers and journalists (of the lay Press) do not even know where to find him. They can write of art, music, travel, even of medicine, quite sensibly; but they publish the most ridiculous news about engineering work simply because they have no immediate access to the engineer. Even when he reads their nonsense the engineer opens not his mouth.

Some years ago a novelist wrote a book in which a power station was described. It was a building filled with immense zinc rods in gigantic porous pots—and that is about as near the public ever gets to us. There is a gaping chasm between. I suppose that if that novelist had inquired at his club for a reliable electrical engineer to inform him, he would in all probability have been directed to the nearest plumber.

I could go on giving instances of the engineer's utter lack of touch with the community for which he does so much, but I think that members will understand what I mean from these few examples.

I am not ambitious enough to propose offhand a detailed remedy for this state of affairs. Like the question of German reparations, it is somewhat complicated. The solution of our dispute with Germany would have been very easy, however, if someone had found a means of inducing in our late enemy a change of heart. Similarly I suggest that the solution of this relatively small engineering problem will best be brought about by a change of mind. I realize that a complete change of mind is the most difficult of all things to induce. Sometimes it takes generations, but I feel that I shall have made some little progress towards my end if I have made members think about the disadvantages of our present situation. An evil clearly understood is already on the way to remedy. No good engineer approves of the idea of advertising in the ordinary way. But in the endeavour to dissociate ourselves from all suggestion of advertising, is it not possible to go a little too far in the other direction?

Our Institution, I think, has followed a happy medium, but there is at least one other body which has made for itself such rigorous laws that their effect simply is "Unto him that hath shall be given." The professional code of the body I have in mind so operates as to ensure that the more prosperous members shall obtain the bulk of all important new work. The enormous lists of work already carried out by these senior members together with their large connection and affluence act as an advertisement, though of course it must not be so called. In consequence the juniors, who have no advertisement of this kind but are nevertheless bound by the self-denying ordinance of their profession, are placed at a cruel disadvantage. The position is not quite without its humour. The greatest opponents of advertising in this body are the seniors who have already secured the advertisement they require.

Besides, there are ways and means of obtaining publicity which do not come under the ban. These methods of advertising are quite efficient, yet they are not discountenanced. It is like betting, which may be carried on if we are careful to bet in a certain place and manner. For instance, there is the expert who makes such a practice of speaking in every discussion that eventually his name becomes as celebrated as if it occupied the whole front page of a daily paper. In fact, it is a much better method, for he not only gets his publicity free of charge but he gets it amongst the very men from whom he can expect patronage. I am not blaming people of this type. From many points of view they are to be commended. I wish that we all of us spoke up more and oftener.

Members will agree, however, that a system which forbids one type of advertising whilst permitting another is not entirely satisfactory. It allows only the more energetic amongst us or the best elocutionists to come to the front. Sometimes it happens that the silent members have something of value to impart, but they have no gift of public oratory. They are "mute, inglorious Miltons," and so they will always remain. This is a defect of many good engineers. They are far too reluctant to speak. It is one of the phases of the question with which any reform movement would have to deal.

I have for a very long time thought that part of a schoolboy's training (especially those that intend to be engineers) should include instruction in debate.

Some members will shudder at the thought of these benches being filled some day by a whole battalion of glib young orators. My plea is not for the wholesale manufacture of hot-air merchants. Talking is too often the negation of doing; but the really effective speaker is the man who gets to his feet only when he has something of consequence to say. Let us hope

that the trained debater of the future will have acquired not only the gift of self-expression but the wisdom contained in the old adage—"Stand up, speak up, shut up."

Were any court of inquiry to hold an investigation, they would come across some surprises. They would find, for instance, that an exaggerated horror of publicity did not conduce to the best engineering work. In the case of the body that I have mentioned the monopolizing of all big new work by the senior members, who are often overloaded and no longer young, means that such work may be deputed to clerks and to beginners. Thus the client is badly served and the reputation of the profession suffers. A reasonable system of publicity would have given the underloaded and quite capable rising men much more of this work to do.

In this connection, a universal defect of engineers is their lack of appreciation of the Press. Here I may say at once that I have taken some trouble to find out how the engineer is regarded by the Press which may be credited with some knowledge of this question of publicity.

The lay Press finds that the engineer is aloof and non-communicative. He fears reporters and gives them evasive answers. Now I contend that instead of ignoring the lay Press, the engineer should consider what advantage could be taken of the situation, not for himself personally but for engineering in general. There may be an opportunity for him to correct some ridiculous impression and to replace a silly description by an accurate one which will stir the public imagination.

Unfortunately this attitude of hostility towards the lay Press is often extended towards the technical Press. Knowing many members of the technical Press as I do, all of them trained engineers and most anxious to fight our cause at every turn, I really think that this is most unfortunate. If something has happened that must not be mentioned, if some project that must not be reported is on the carpet, the best way to deal with the technical Press is to make them fellow conspirators. Tell them exactly what the mystery is if we possibly can, and put them on their word of honour not to print a word; but do not do this needlessly and frequently or they will grow tired of it. There are so many things that might quite easily be told to the Press, yet are withheld out of a spirit of distrust or lack of sympathy or fear of responsibility.

Bureaucracy is often at the bottom of this uncommunicativeness.

The reason why it is so difficult to obtain interesting news from some of our big manufacturing firms is that every official is afraid to mention facts before consulting the next official above him, and as this system ultimately leads to the managing director, who may be in the South of France and have a dislike of all newspapers, nothing but uninteresting or misleading information is available to the Press.

The bigger a British concern is, the less are its personal sympathies and the smaller is its appeal to the public, even to the technical public (ourselves).

That is a rather serious state of affairs for this country. Big manufacturing firms in America fully recognize the value of publicity and go out of their way to publish news. The American public are permitted to know the service that the engineer can offer them, and that means increased business not only for American engineers but for America generally.

The failure of the British engineer to appreciate publicity has grave disadvantages. As a result he suffers in status, in public esteem and in remuneration; more than that—the products constructed by his genius are restricted in quantity.

Not only are engineers at fault as individuals. When they band themselves together in technical bodies they are usually driven by a desire for the approbation of their own kind to forgo the approbation or even the notice of the public who are their customers.

Further, when engineers combine to form a big trading and manufacturing concern, the bureaucratic spirit of its officials and the consequent fear of responsibility tend to cut off all communication with the firm's clients. Such news as clients receive is obtained only from the catalogues.

In fact, turn which way we will in the British engineering field, whether to individuals, to certain professional associations or to great trade groups, we find that the conditions invariably tend towards the isolation of the engineer and all his work. The public who are so deeply indebted to him and from whom he obtains his living hardly know of his existence.

It seems to me that it is a totally wrong and unnecessary situation. I believe it largely accounts for the fact that although the British engineer is the best in the world, he is very far indeed from being the best appreciated. It accounts for the fact that the legislators penalize him and that in many cases non-technical officials succeed in making him a subordinate.

The engineer up to the present has been too silently doing his work; but add to his training the art of self-expression and nothing can prevent him from taking his place at the head of affairs—whether it be in Parliament, in industrial life or in town councils—where most of the money expended is for work that will eventually be done by engineers. If one looks at the lists, one will notice how many lawyers are in Parliament. Their profession requires that they can speak lucidly in public. But how many engineers do we find in Parliament?

I hope that the engineer of the immediate future will see his opportunity and assume his natural right to direct as well as to construct. If he has the advantages I have spoken of—the trained mind as well as trained hands, the sound knowledge of finance and modern business methods, and finally the power of self-expression reinforced by practical knowledge—with all these advantages he cannot fail to influence the course of events and so render invaluable service not only to his profession but to the country as a whole.

NORTH-EASTERN CENTRE: CHAIRMAN'S ADDRESS

By THOMAS CARTER, Member.

"THOUGHTS BY THE WAY."

(ABSTRACT *of Address delivered at* NEWCASTLE, *22nd October*, 1923.)

ENGINEERING.

When Thomas Telford and others of the loving subjects of King George the Fourth formed themselves into a Society for the general advancement of Mechanical Science, their object was to promote the acquisition of that species of knowledge which constitutes the profession of a Civil Engineer, being the art of directing the Great Sources of Power in Nature for the use and convenience of man. We are all civil engineers in the original sense: the title was used to distinguish its holders from military engineers, who were the only engineers from their first coming to England with William of Normandy in 1066 right down to the eighteenth century. When we remember that it is only about two hundred years since the modern engineering movement in Britain began, and when we think how to-day it permeates the whole national life; when we recall that whereas the early engineers had to grope in the dark for information and help, everyone of us has the chance of learning more than they ever knew, though few of us have the wit and the brain to snatch it; when we recollect that at first engineering was not thought to be a gentlemanly job, but that King George the Fifth himself is now our patron, we begin to realize the enormous change that has taken place in what is but a day or two of the history of the world. So we go from stage to stage: John Bright said truly that we stand on the shoulders of our forefathers and see further. This twentieth century has already witnessed amazing developments: aeroplanes, not long ago things that we almost broke our backs to see as they flew above us, became as common as sparrows during the war, although the first flight from England to France was accomplished only in 1909; moving pictures, exhibited about 20 years ago as a scientific novelty, have now become a necessity, it may be of sometimes questionable value, in the lives of millions, requiring, in place of two licensed cinematograph theatres in London in 1909, no less that 289 in 1919; a huge industry has arisen in the motor-car trade; wireless telegraphy and telephony are sturdy youngsters rapidly growing up; ordinary telephony, the other and older form of a most marvellous thing, is coming more and more into use even in this country. It ought not to be forgotten that many of these things increase the complexity of affairs, and add to the difficulty of doing ordinary business thoroughly and with due thought, because they hasten everything and speed up the rate at which we live. All this is inevitable, no doubt; but in taking stock of our blessings, we must count their cost and strike a proper balance.

THE LAST TEN YEARS.

We may spend a little time usefully in reminding ourselves of a few of the far-reaching changes brought about during the last ten years because of the war, with its never-ending influence, as well as in the normal course of the development of things. Japan (very much in our sympathetic thoughts lately), starting from a foremost place in the Far East, has forged ahead enormously, her foreign trade increasing from 92 millions sterling in 1910 to 438 millions in 1920. Europe itself is utterly changed, with kings overthrown, and with new and in many instances hitherto untried methods of government set up. Europe was the creditor of the United States before the war for 4 500 million dollars, but owed the United States 13 500 million dollars in 1921. In our own country the cost of living is still about 70 per cent above its pre-war value. As a nation, we spent about 134 million pounds in 1900; in 1913–1914 the total had grown to just over 200 millions, while in 1922–1923 it was not far short of 1 000 millions. There is, too, a deadweight debt of over 7 000 million pounds claiming interest and redemption at the rate of about 350 millions per annum; while the 7 000 million pounds are mostly war pounds of low value, we must pay the charges at a fixed percentage rate, in pounds of now greater value, relatively, therefore, more difficult to obtain.

It is calculated that more fuel and iron were taken out of the earth during the ten years from 1911 to 1921 than during the whole of the nineteenth century; and we are still tending to use our resources at too great a rate. The study of fuels, however, is attracting special attention; low-temperature carbonization of coal is being investigated as a means not only of increasing efficiency but also of improving the state of the atmosphere by the avoidance of smoke. Having squandered our fuel almost without thought for so long, we can scarcely pride ourselves on our desire to lock the door of the stable now before the last hair of the horse's tail has finally passed outside; but let us take it as a sign of grace, and encourage it in every possible direction.

THE FOUNDATION OF THINGS.

Engineers above all other men need the spirit that will overcome difficulties. It is the faith that expects to finish a job some day that is the justification for ever starting it at all; that is what we need supremely. More particularly is it needed in that abstruse branch of engineering—I am right in calling it engineering, am I not?—that for forty years has been seriously tackling

the question of the mechanism of the universe. Man has found out very little as yet; what we can learn from the past, wonderful though it be, is as nothing to what is waiting to be revealed in the future. The man with the most profound experience of how things may work is of necessity the humblest of all men because he knows that he does not know.

The warp of the universe is unrolling itself from moment to moment so that we may help to complete the pattern worked out for the endless piece. Some of the pattern we have discovered, while some is not yet clear; moreover, some that seemed clear in the past is no longer entirely so; and we are coming more and more to regard all theories as provisional, and as open to possible revision at any time. We are as the blind would be who tried to read a book printed in Braille type without having been taught what the symbols stood for; even if they had been told the story a little they would have to find out the meaning of the symbols as they went along before they could follow it word for word. No more fantastic than that was the undertaking of Lord Kelvin when, following earlier speculators, he set out to propound a definite view of what the atom might be like; his work has been continued by J. J. Thomson, by Rutherford, by Bohr, and by many others of enormous courage, each drawing the curtain aside a little more from the final picture.

Some Technical Problems.

Much attention has been given from time to time to output coefficients, mass factors, or size factors, as they are variously called, these being expressions that attempt to set out the relation between output and dimensions. The usual assumption for dynamos and motors is that their output depends on the volume of the rotating part, that is, on its diameter squared multiplied by its length, commonly known as its d^2l; and the statement is ordinarily given in the form of a curve connecting d^2l with watts per revolution per minute. It has been too little emphasized, though Carus-Wilson in 1898 and others before and since have pointed out, that watts per revolution per minute is an expression not really involving the idea of speed at all. Watts are work per second, measured in joules per second, and hence the watts per revolution per minute are 1/60th of the joules per second divided by the revolutions per second, that is, 1/60th of the joules per revolution. But the work per revolution done by a rotating body is, numerically, equal to 2π times the torque exerted by it; hence the watts per revolution per minute are $2\pi/60$ times the torque of the rotor in units corresponding to joules, that is, $(2\pi/60) \times 10^7$ times the torque of the rotor in dyne-centimetres. Torque has nothing to do with speed, but it is merely the product of the radius of the rotor and the total tangential force exerted on the surface of the rotor by the interaction of the magnetic field of the machine and the current in the rotor conductors. As is well known, the important constants in an electrical machine are the ratio of pole span to pole pitch, the flux density in the air gap, the ampere-wires per unit length of rotor periphery, the diameter and the length of the rotor core, and the speed of rotation. Heating problems, and commutation problems in machines with commutators, determine the possible relations of these constants to one another, but the general statement, always true, is that the watts of a machine are the product of π^2, pole-span ratio, air-gap density in lines per unit area, ampere-wires per unit length, rotor diameter squared, rotor length, and speed in revolutions per minute, divided by 60 and by 10^8; or, in symbols,

$$\text{Watts} = \pi^2 \psi B_g a_w d^2 l n / (60 \times 10^8).$$

This is independent of the unit of length so long as all the quantities are expressed in the same unit. Taking direct-current machines as an example, I have found that the air-gap density and the ampere-wires per unit length of periphery may be expressed by purely empirical formulæ as quantities dependent on the rotor diameter, and when these empirical expressions are substituted in the general formula, it becomes :—

$$\text{Watts} = (1/205)\left\{d^4/(d + 16\cdot5)(d + 33)\right\} ln,$$

when d and l are in centimetres, and

$$\text{Watts} = (1/12\cdot5)\left\{d^4/(d + 6\cdot5)(d + 13)\right\} ln,$$

when d and l are in inches. These empirical formulæ have no real physical meaning; they merely happen to fit certain facts with some approach to accuracy.

In passing from the question of output coefficients I would suggest that the different opinions held about this, as about every other problem, arise from the different personalities of the holders. We all stand and look at the same thing; no two of us stand at the same point, and consequently different aspects are presented. The trouble is that each of us swears that he has seen the whole thing; it is the old story of the two knights and the shield over again, and I believe that this explains the different philosophies, religions, schools, and political parties that have existed since the world began. There are things that matter, about which we all agree that we dare not compromise; there are things essential to the stability of the nation that we must accept and do, whether we like them or not; but many a question, seeming great to those who strive about it, so great that it obscures the light of day, could be settled in a word if it were but realized that there must always be a relativity of view, and if some attempt were made by the disputants to change places one with another in an endeavour to arrive at some common acceptable conclusion—an honest and courageous endeavour, with no turning of a blind eye to what it is thought should be invisible.

Industrial Problems.

Most of us know far too little about economics; economic science is largely experimental and empirical because its data are changing from day to day with changing conditions, and it must adapt itself with perfect flexibility to things as they are before it can attempt to advise on the future. During the war, when apples were very scarce, I saw one, only one, on a plate in the fruit stall at King's-cross station.

I asked the girl in charge how much she wanted for it; and she answered, "A shilling." "Is it really worth it?" I asked her. She said, "If you want it enough, you will pay a shilling for it." I am not an expert in economics, and neither, I imagine, was the girl; but I am sure that she summed up a considerable part of it all in her answer. The relation between cost prices and selling prices; advertising campaigns to create and to stimulate desire; the advisability or otherwise of a corner in wheat; are not all these regulated and determined by the very principle enunciated so light-heartedly about the apple? So it is that now and again some mysterious Saharavitch or Braunschild or Stonyfellow, sitting at the centre of his web of vast financial dealings, can so control the threads in accordance with these very needs and desires of ours that a touch of his finger sends some of the mighty to ruin and raises up others from obscurity to take their places, while he himself is more powerful than them all.

It would be entirely out of place for me to say anything in detail about modern industrial problems, linked as they are to so great an extent with highly controversial questions at home, and dependent as so many of them are on international affairs of so wide and complicated a nature that we dare not enter on them now; but although we cannot suitably undertake a particular examination, we may pause to recall one or two general principles. If we take, as one out of many possible examples, the relation between employers and unions of manual workers, must we not think of it as having arisen out of something that was originally very like the relation between father and son? The old days—in many ways, though not in all, the better days—witnessed a fatherly interest in his apprentices and his journeymen on the part of their master, and on their side a feeling of gratitude for much knowledge imparted to them. Let us carry down the simile, and remember that only fifty years ago, a mere nothing in history, did we begin in any real way to think that all children might be worth a general education. That was an almost frightening experiment. There have been, and are, all sorts of mistakes in carrying it out that only the further education of the educators will remedy; and, meantime, a vast nation of rather crudely instructed people has arisen, so few of them having grasped any essentials, and so many of them wanting heaven before they are ready for it, that earth is like to become hell for us all through sheer lack of knowledge of how to steer clear of slippery downward slopes. Now let us think together: if our sons and our daughters, not long at school and with just enough knowledge to make them imagine they know everything and want to rule everything, come and tell us that we are old fossils, that we don't know what is good either for us or for them, that our sort of people has had its day, but that in their magnanimity they are willing to blame the system that produced us rather than us ourselves, do we then and there hale them before the magistrate for breach of contract? Or, if we suggest to them that some things might be better done, do they say that we are trampling them to the dust and are not fit to be their parents? Often enough there is anger and sternness, I agree; but in the great majority of these troubles, anger and sternness are moderated by a sense of fitness that recognizes the equal humanity of the temporary antagonist and the certainty that all our lives are so interwoven that the good and the hurt of one are the good and the hurt of us all; and a friendly talk, with a will to agree on both sides, smooths away the difficulties and leads to a lasting good understanding. I venture to suggest that the very same broad principle would settle many terrible troubles in the industrial world if it could but be applied; and why not?

I fear that political and parliamentary interference in these matters is almost necessarily bad; Parliament does not undestand the problems. Industry itself must somehow devise the means for the solution of its own problems, and the first step is to realize that every man, every class, every group, every party must hold individual views, destructive, perhaps, of each other, until some wider and better view is put before each of them and is made so attractive that it will lock them all together in a determination to find a way out of their darkness hand in hand. We hear much of the demand for a fair day's pay for a fair day's work; but the implication of that, not always fulfilled, and not always even remembered, is that a fair day's work is going to be done. I do not speak without knowledge when I say that a sitting down together, with goodwill all round, will lead to almost amazing results to the advantage of all; I have the best of reasons for knowing the splendid effect of mutual loyalty and trust and support. Sentiment, the cynics say, has no place in business; I say it is a lie, and a very stupid libel on humanity. If every man in industry really made up his mind to think of industry before himself, what a revival there would be! And how beneficially it would react on himself; for, as always, the seeking of the greater things causes all the rest to be added as a gift. The success of industry inevitably is the greatest interest of all of us. The more we have ourselves of knowledge and education and training, the more may industry, and the nation itself, rightly demand from us. The times are changing, and many ancient things are being shaken: let us see to it that the world is carried across from the old to the new on the broad shoulders of men of understanding.

Other Problems.

I am sure that engineers ought to be more in public life than they are; many problems have to be dealt with there that would be more fitly solved if engineers, with the advantage of their knowledge, training and experience in large affairs, were in a position to advise and had some say in their settlement. One of the strange and disturbing things about public life at present is that those who enter it to govern others often show by their public actions that they are unaware of the first principles of how to govern themselves; I feel that here the engineer's habit of dealing with intricate problems dispassionately might serve to counteract much violent haste that only slows down real progress towards what it would achieve.

Much that is known has not even yet been written down in books, and although we are far from the days

when each man had practically to begin at the beginning and find out things afresh because there were no records, there is a refinement in work and a skill in craftsmanship that cannot be acquired except from those who have themselves learned from a still older generation in their youth and so make us the heirs of centuries if we learn from them in our turn. When our interest is first awakened we are all eager to learn, and our undisciplined efforts are absorbed in copying others: only later do we pass through a stage of more precise understanding to generalization and invention and discovery for ourselves. How vitally, therefore, it matters that the foundation should be well laid at the beginning; and if we find an older man, willing to help us because we are young, how much more secure will the end of our work be!

The Training of Engineers.

Education cost us as a nation over 19 million pounds in 1913–1914 and over 55 millions in 1922–1923; yet Professor Burnett of St. Andrews, in his Romanes lecture at Oxford, expressed the view that ignorance is increasing to such an extent that there is a possibility of another dark age. Professor Burnett also warned his hearers against thinking that "there existed somewhere a stock of ready-made knowledge, which had only to be doled out liberally to satisfy all needs. That was altogether wrong. . . . What could be supplied from stock was merely the sediment of dead knowledge, though even that was valuable, since it furnished us with the necessary tools for the real activity of knowing. But it was not itself the real thing. The only knowledge worth distributing was living, first-hand knowledge." Anthony Trollope remarked to Miss Dunstable, who said that one doesn't ponder over soap bubbles, "Pardon me, Miss Dunstable, one does, but nine hundred and ninety-nine do not." Hence we have so terrible an occurrence as the grave statement in a newspaper that scientists are seeking a new ray with which they will "defy the normal law of gravity." What do people who say these shocking things think the law of gravity is? And how do they propose to "defy" a natural law, when all they can do is to prove it right or wrong? The hopeless confusion between a political law, which is merely a public sanction and may be defied and disobeyed, and a natural law, which can no more be defied or disobeyed than rhomboids can be argued with and cajoled into looking more like pelicans than they do—this confusion, I say, would be ludicrous if it were not symptomatic of the state of much current so-called knowledge.

I want to suggest that, important as is the provision of the right sort of education for those who offer themselves to be educated, it is even more vital to select for that education only those who can use it properly. If the community allows us to be born and to grow up, it is, I maintain, its bounden duty somehow to see that we are offered the sort of life to live that will be best both for us and for it. The aim of all education ought to be, first, to fit us for our share in the general work of the state as citizens, and second, to prepare each of us for some individual contribution to that work according to any particular fitness we may have. Without resorting to specialization at too early a stage, skilled teachers ought to be trained to discover the characteristics of the children in their care, so that eventually engineers may be educated as engineers and not, for example, as drapers, and, on the other hand, one who should be getting ready to write books may not by accident stray into the engineering course of some university. Provide means for educating engineers; but see that engineers are provided also. Under such a regime as that we should be able to pay our duty to the State in return for the right to live our proper life.

We dare not send down our designs into the works bearing the legend "We think these are correct"; we must be sure, for the construction of a machine is not like a book-keeping transaction in which an error can be corrected, or like a wrong payment, which may be adjusted by the passing of a cheque. A slide-rule is the servant of a brain, not a substitute for one; and the compression of calculations, like the compression of the results of the work of centuries into a few laws and expressions and formulæ, is a worse source of pitfalls and a more fertile field for the springing up of mental sluggishness than most other things. Short cuts are only good when we know where they lead to, and even then they may rob us of the experience that comes of going round the longer way that may bring us sooner home.

Purely intellectual training is to be shunned: it limits and binds and confines. The pure theorist cannot go out into the world of commerce and meet his fellows, mostly not pure theorists, with any chance of success. For that reason, the purely technically trained engineer is unfitted in most instances to sell the machines he designs or builds; to his theory must be added knowledge of men and of their ways if he is not to be beaten every time by the keen man trained to deal with human beings in the very practical school of contact with them. The sense of when to compromise and when to win by appearing to yield or by actually yielding is only certain after much seeking for it. Two precious possessions are the ability to suffer fools gladly, and the knowledge that you do not yourself inflict on the other man that painful need. Things to pray for are the instinct for the right moment and the realization that to arrive at the wrong moment may be fatal: the early bird, on the spot at the proper moment, got the worm; early arrival is not the lesson of that proverb, for the worm, which must have been there even earlier, got the bird, if I may put it so, and was destroyed.

Let us realize supremely that the man who thinks that his training has come to an end with the end of his apprenticeship or when he has gained a university degree is already as one dead and altogether damned; the only live men are those who seek to learn from every occasion something that will serve them well in the future. And of these live men they will live longest who remember that it is not so much achievement that brings happiness as the striving after it, and that "merely to pass through experiences is nothing, but to preserve a clean heart amidst all that comes is everything."

CONCLUSION.

Even if we forget the wider, greater, higher things—the stars, attracting us less than the signs that flash in Piccadilly-circus; the immensities of space, impressing us less than the enormity of our own wonderfulness; the music of the spheres, less distinct to us than the brawl and noise of this present life—nevertheless these rich beauties are always around us, to be seen sometimes when for a moment we open our eyes, and to be used then to refresh us and to keep us from being uglier than we might be. And if we contemplate more frequently those unseen realities that are eternal we shall be caught up into a higher view of what we may accomplish; some of life's discords will resolve into a grand harmony; we shall understand better that while of most things it must be said: "And this also shall pass away," we may view their passing with serene calmness because the few things that remain are sufficient for us; we shall not have to say to ourselves when we have done all that was commanded us: "We are unprofitable servants; we have done that which it was our duty to do," for we shall have recognized and tried at least to do the little more that counts for so much.

Hear, finally, one of Robert Louis Stevenson's "Prayers written at Vailima"; and let us try to catch its spirit for our guidance. "The day returns and brings us the petty round of irritating concerns and duties. Help us to play the man, help us to perform them with laughter and kind faces, let cheerfulness abound with industry. Give us to go blithely on our business all this day, bring us to our resting beds weary and content and undishonoured, and grant us in the end the gift of sleep."

IRISH CENTRE: CHAIRMAN'S ADDRESS

By ROBERT N. TWEEDY, Member.

(ABSTRACT *of Address delivered at* DUBLIN, *24th October*, 1923.)

If some years back this Irish Centre was languishing, it was not because the parent Institution neglected her child, but because the Centre itself could not sustain at full brightness the glow of life with which it was endowed. Members did not produce enough papers out of their native ranks, they were not over-energetic in importing papers, and many of them did not read the *Journal*, although they all grumbled that it was the only return they received for their subscriptions.

Doubtless there was an ever-growing need of reforms, and the most urgent need of all was closer contact, greater intimacy between the parent body and her outliers; but, ever since close contact has been established,—and for this I think we ought to be particularly grateful to those who have occupied this chair during the past few years—we have felt perfectly confident that the Institution is ready and eager, not only to do full justice to her outliers across the narrow seas and the wide oceans, but to make sacrifices for them.

Our parent Institution recognizes full well—and did not need to be forced to recognize—that motherhood has responsibilities as well as rights. Her children recognize on their part that they are bound to her by real ties, which, however, are intangible, and in a great measure indefinable. They vary in their nature and strength with each individual, according to his temperament.

While one man may find pleasure in belonging to the Institution which claims Kelvin, Siemens, J. J. Thomson, Hopkinson, Fleming, Lodge, and a host of other famous men, another will feel an affectionate pride because he is derived from the nucleus of learning and experience from which vital cells innumerable have been distributed over the whole world; and a third will delight in the reflection that the hall-mark set upon his technical ability adds authority to his zeal for the education of his fellows.

The Institution was founded "to promote the general advancement of Electrical and Telegraphic Science . . . and to facilitate the exchange of information and ideas on these subjects amongst members of the Institution and otherwise. . . ." If there could be anything essentially non-national anywhere it is the Institution of Electrical Engineers. It is extra-national, not national or even international. Flags, policies, tongues, colours, sex, opinions, are all one or all nothing to the true spirit of the Institution. It exists solely as an instrument for the promotion and exchange of technical culture for the world at large.

The fact that the majority of the members of the Institution resident in Ireland are citizens of Saorstát Éireann, while the remainder are citizens of Great Britain, should not weigh with the members resident here or elsewhere, and certainly would not weigh with the Council. Goodwill and allegiance to the common banner of scientists throughout the world, vague though it may sound, is the sublimated purpose of the Institution to which we belong. Boundaries, barriers, political

prejudices, and national feuds sink far below our horizon when we meet in Council, or Committee or open session. We meet then not as citizens of any State, but as citizens of the world at large, charged by the spirits of the glorious pioneers of our vocation to continue their work for humanity.

In Ireland we have no well-established traditions in electrical engineering, such as exist in all industrial countries, and that disability works covertly against us. As the resources of the country are developed that lack of accumulated tradition will become a danger unless Irish electrical engineers have anticipated it by taking suitable action.

I can see no better way and certainly no easier way than the hard-beaten high road over which so many thousand electrical engineers have passed since 1883, when the Institution absorbed the Society of Telegraph Engineers and Electricians. The tradition of the Institution is continuous and complete from the days of the earliest telegraphic circuit and the first electric lamp down to the present moment. It is not an English tradition or an Empire tradition but a world tradition. Irishmen will not be degrading their regained liberties by adhering to the Institution which has meant so much to civilization as well as to the profession and the industry of electrical engineering. On the other hand, if we support it feebly or not at all it will be many years before we shall have built up an independent analogous structure attractive to the new generations as they arise, and carrying weight with the Irish public.

The electrical engineer, whether he be an adviser or an executant, but in either case a man properly qualified to undertake work of importance, finds his path beset with numerous abuses and overgrown with the weeds of prejudice and ignorance. The legal and medical professions overcame similar obstacles to progress and public safety by strengthening their guilds, and there is no other solution for us.

I feel that this session may be the most critical time in the history of the Irish electrical profession, and I offer no excuse for turning my address into a sort of domestic homily. The members of the Irish Centre of this Institution have the clay of the future of their profession in their hands. They must mould it as they will. Let us be guided in that moulding by thoughts which have passed through a filter close-meshed enough to reject all but those considerations which will ennoble the profession, and, in so doing, benefit our brethren in Ireland, in the British Commonwealth of Nations, and throughout the world.

Decisions ought not to be made by individuals or by groups within the Centre. The Irish section of the profession should adopt no policy until the whole Irish Centre of the Institution—not the Committee acting alone, nor in Northern Ireland alone—has threshed out the whole matter frankly and openly. The Institution cannot, of course, be a party to its own dismemberment, or to an official discussion involving a question of dismemberment, but it is assumed that the majority of qualified electrical engineers in Ireland are members of the Institution. Therefore the easiest way to reconcile opposing views within the profession in Ireland is by meetings of the Irish Centre.

We must remember that the problem before us is rather terrifying in appearance because it has two heads springing from one trunk. Obviously that is an abnormal phenomenon in science as well as in nature, and the problem involved is first of all to get both heads looking in one direction, and then to metamorphose them into one normal head of benign appearance equipped with a single active intelligence.

In plain unfigured language the Irish Centre should do everything in its power to prevent its disintegration either through the defection of members to form a purely national body within Saorstát Éireann, or by reason of the refusal of members in the north to work with members in the south. Mutual understanding and unalloyed goodwill are the only instruments through which our purely scientific aims and objects can be made to transcend and obliterate political divisions. There must be no whisper of sectionalism in our councils, but councils there ought to be. Personal contact is the finest solvent of human differences, and the Committee of the Irish Centre must set itself to discover some method of contact.

One has to admit with profound regret that there is an almost entire severance of continuity between the northern and southern sections of our Centre. Technically one, we are actually separated, although the outgoing Committee did everything it could do to throw a bridge of fellowship across the gap. Given goodwill everything is possible, and it is the great task before us this session to create or to foster that quality. Our two past-chairmen when attending the Council meetings in London took every opportunity to dispel the somewhat distrustful atmosphere which seemed to exist in the northern part of this Centre, and I shall continue an effort which must have a good effect ultimately. The main work must be done here, and the first thing to do, in my opinion, is to obtain at first hand a statement of grievances in order that the Committee may see what can be done to redress them. Speaking for myself I should like to see several northern members on the Committee, and at least one meeting out of three held in Belfast or Derry. If that were done we should get more papers from Irish members, and we could have a meeting every fortnight during the session instead of about once a month. There might not be a considerable attendance of members at these meetings, on account of the distance to be covered, but there would be immeasurable satisfaction in the thought that the electrical minds of the country were working together, planning an identical programme of much wider and more mutually beneficial scope than would be possible for two anæmic Centres in a small country poorly developed in the engineering sense.

The second head of the problem upon which I am touching takes the form of a suggestion which has been made that Irish electrical engineers should secede from what is termed an alien Institution. I think every man should ask himself what value he attaches to his personal connection with the Institution. Unless he is careless about money, it is to be presumed that the least assessment he can make is that the letters M.I.E.E. or A.M.I.E.E. are worth the current subscription, otherwise he would have resigned his right

to use those letters after his name. There is, then, definitely, a certain amount of prestige or status attaching to the bearer of the letters. The member can come nearer the true estimate of value if he will answer for himself the question: "Would I abandon these letters for the letters of some other Institution, native or foreign?" Maybe he would, in which case there is nothing more to be said, for he will believe, justifiably enough, that neither he nor any other member of the Irish Centre will be damaged by secession.

If he has the courage to admit to himself that he would not abandon membership, I think he should probe the matter still farther as an altruist. He should say to himself: "It is true that I value the advertisement to the world of my qualifications by the display of these letters, and so long as I pay the current advertisement rate I am entitled to display them and shall display them, even in preference to those of the strictly national body which I intend to set up? I can use my title with due effect not only in Ireland, but wherever I travel or settle abroad. But what about the youths of this and the next few generations? I may adhere for practical purposes to my comparatively narrow new society, and continue membership of the I.E.E. merely for its advertisement rights, but I must do all I can in loyalty to induce young engineers to enter the Irish Society rather than the Institution. If I do that successfully, what will be the status of those young men from the advertising point of view when they are competing for positions in Ireland? Furthermore, seeing that these youths cannot be bound like the old-time serfs to Irish soil, what will be their status in respect of competition for foreign positions?"

When our friend has proceeded thus far with his intimate inquisition it may be necessary, depending upon the answers he has given to the foregoing questions, to put others. For instance: "Is it worth while to enter Ireland in a kind of race for professional prestige against the mother of all scientific electrical institutions? Have we any chance against a de-nationalized—in other words, a truly scientific—Institution already numbering more than 11 000 members throughout the world? Is it even worth while setting up a subsidiary or auxiliary institution for the sake of having it national? Would it live? Would it deserve to live from the scientific point of view?"

"But," says someone, "was there not only the other day an instance of the Institution interfering in Irish politics? What was this Committee of the Irish Centre which presumed to advise the Government in drafting the Electricity Undertakings Bill?" Let it be understood at once that this is not even half a truth. The Institution is not empowered by its Bye-Laws, as I read them, nor by its Charter, to take hand or part in legislation. In the case in point the Council of the Institution absolutely vetoed any action by the Irish Centre which could be construed as interference of any kind. What actually happened, and what may happen again, was that the Government official who was entrusted with the arduous and highly technical preliminary work upon the Bill, sought the advice and assistance of the Chairman of the Irish Centre, selecting him naturally and properly enough as the focus of the profession in Ireland. He was bound to refer the matter to the Committee, who in their turn referred it to the Council. The Council ruled that the Committee of the Irish Centre could not act in the manner suggested, but that it was competent for the Committee to put before the Ministry concerned names of members who would act as an *ad hoc* advisory Committee upon their own initiative and responsibility and without reference to the Institution or to the Committee of the Irish Centre. This suggestion was accepted by the official in charge of the Bill; a Committee was formed, and is understood to have done useful national work as a group of citizens with a particular form of prestige attaching to them by virtue of their membership of the Institution. Nothing, it seems to me, could have been more correct; nothing more suitable as a precedent for the future.

I submit that it is nationally, ethically and professionally, right for citizens of any country to give advice, or to offer to give advice to the Government of their country upon technical matters in which they are, by implication, expert. I should consider it an uncitizenlike action to refuse or to withhold such assistance. That a Society or Institution should give advice ex cathedra, even if it is empowered to do so, is open to grave doubt, and there can be no shadow of doubt that an Institution originating in one country, however international its purposes may be, would be acting not merely unwisely but impertinently if it should presume to advise the Government of another nation. That applies with equal force to the Institution *vis-à-vis* the components of the British Commonwealth of Nations, as to the Institution *vis-à-vis* France, or Russia, or the United States of America. Nevertheless a Government might ask, without derogating itself, for technical advisory assistance from the resident members of that Institution which had the greatest prestige amongst the nations. In Ireland, I take it, for many years to come that Institution would be the Institution of Electrical Engineers to which we have the honour to belong.

As our industrial side grows we may expect to receive accessions to the Irish Centre from across the waters, engineers normally resident in other countries, but we should aim very definitely at keeping the Institution constantly before the growing generation. There should be something done by way of propaganda in the technical schools and universities, and this much more in the interest of the budding engineer than in the interest of the Institution. The earlier a young man becomes familiar with the Institution by studentship, the sooner he is likely to pass through the ascending grades to the full membership to which he is sure to aspire. The presence of Students and Graduates of the Institution at our meetings is desired and appreciated by the committee, and I hope that the programme for this Session will attract them and will induce them to bring others who are not yet enrolled upon the Institution lists. When our roll of Students becomes sufficiently long we shall ask the Students to assist us in organizing a special Students' programme, and I think that might include with much advantage visits to many electrical stations and factories which have

lost their appeal to the older members. The Irish Centre acting collectively could do splendid educative work, not only for prospective and selected Students but for the public at large.

Last session I outlined a power policy for Ireland, and nothing has happened since to weaken my belief that our financial credit depends largely upon the adoption of a policy of that kind. The way in which the Liffey scheme is handled by the Government is of enormous importance to the country. It is the first large scheme in the Saorstát, and I tremble to think of the national issues which hang upon it. It is of far more than local importance, and I am not at all happy at the thought that the Government may be content rather to await the outcome of the silent struggle between the several interests which wish to develop the Liffey Falls, than to tackle resolutely the problem of which this scheme should be a part. Ultimately it would be but a small part, but its present importance is so considerable because it is the originating nucleus, and because it is of immediate interest to the capital city.

The credit of this country is just as much or as little as its citizens like to make it. Superficially it seems to be low at present, but I have never faltered in my belief that the possibilities were never greater, and that the engineering profession has graver responsibilities and brighter prospects before it than any other section of the community. Unity of purpose, unity in action, and a clear conception of the goal are all needed, and are all attainable by goodwill and the sacrifice of self to service.

Two events which have occurred recently ought to be sufficient in themselves to remove the gloom which was settling upon the electrical profession and trades. I hail with joy the first number of *Irish Engineering*, and you will join with me, I know, in congratulating those who are responsible for the new venture upon their courage, their delightful optimism (which in my opinion is entirely warranted) and their really astonishing ability as publishers and editors. For years we have felt the need of an Irish journal which on the one hand would keep us in touch with progress in all parts of the world, with particular reference to Irish conditions, and which on the other hand would act as an effective ventilator of subjects which are stifled or stunted unless they are bathed in an atmosphere of crisp, practical and wide discussion. The advent of this journal is of good augury, and every engineer should feel himself bound to support it by every means in his power.

The other excellent augury is the establishment of the Electricity Supply Association of Ireland, which appears to be thoroughly representative of producers of electricity. Such an Association may grow to have enormous powers in a modern State, so one prays that this Irish Association, formed in the first year of our independence, with developments of unknown magnitude before it, will be guided and inspired in all things by that sense of community service which needs development infinitely more than our material resources, because it has relation to that fundamental sense of religion in man, which is in some danger of being torn out by the roots.

I would suggest to that Association the urgent need for pressing the Government, both in and out of the Oireachtas, to press forward certain recommendations that have been under consideration for a long time.

Possibly the most important of these, and the simplest and cheapest to put into effect, is the organization of a Hydrometric Survey. Another is the Geological Survey of the very partially and inadequately explored coal measures with numerous borings; and the third is to continue and to prosecute vigorously the admirable work upon the utilization of the Irish peat deposits, which has been carried so far by the British Fuel Research Board. In that connection I draw attention to the Report for the years 1922–1923 which leaves no doubt in my mind that the large-scale production of peat fuel in Ireland calls for nothing now but native ingenuity applied to the special and unique problem of devising apparatus for getting the whole of the peat out of bogs ranging from 20 ft. to 35 ft. in depth. The problem has been solved already for the shallower bogs of other countries. Surely we shall not be baulked by this embarrassment of riches!

All these things are rendered the more urgent by the deplorable conditions which persist and worsen on the Continent and in England. As the outlet for foreign trade decreases we shall be forced to become self-dependent to a greater degree than we are at present, and unless we anticipate this shrinkage by hastening the development of our internal resources we shall become impoverished to an extent which I do not like to contemplate.

In conclusion, I want to refer briefly to one phase of the useful work which this Institution might do. Our immediate past-Chairman brought before the Committee the question of standards in electrical engineering, and a meeting representative of consulting engineers, manufacturers and contractors was convened to consider the matter and to make recommendations to the Committee.

The subject has for many years attracted much attention in England, and there is a mass of information available for our guidance. Time does not permit me to do more than express a hope that a matter of such moment to everyone of us, and of even greater moment to the user of electricity, will be pursued with energy during the present session.

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE: CHAIRMAN'S ADDRESS

By E. M. HOLLINGSWORTH, Member.

(ABSTRACT *of Address delivered at* LIVERPOOL, *5th November*, 1923.)

The optimistic prophecy of a universal cheap supply of electricity, to be given from a limited number of "super-stations," has not been fulfilled, and the introduction of the 1919 Electricity (Supply) Act has not, to any great extent, brought about the improved conditions then anticipated. At the same time, there has never been more anxiety to effect improvements, and the great necessity for conserving coal and generating electricity on more economical lines has brought about many advances in power station practice. The most notable of these advances, which I propose to survey in this address, are the application of higher steam pressures and temperatures, the more satisfactory treatment and heating of feed water, the increased speed of turbo-generators for a given output, and the stage reheating of steam.

Regarding the movement in the direction of extremely high steam pressures and temperatures, it cannot be said that those concerned lack courage; on the other hand it has to be admitted that our knowledge of the properties of metals to withstand such conditions is still very imperfect. In other words, the advocates of high limits have outpaced the metallurgists, and the question arises: Will the gain in thermal efficiency be obtained only at the sacrifice of reliability? The test of service alone can answer this.

Regarding the selection of site for a large power station, the advent of the extra-high-voltage cables of large carrying capacity has eliminated one of the difficulties of this problem, in that proximity to the load centre is no longer necessary. The factors of importance are: An abundant supply of cooling water, facilities for railway transport, and large areas adjacent for the storage of coal and disposal of ashes.

Recent practice in the design and lay-out of stations has, generally speaking, evolved a standard type of building having simplicity as the main note. The boiler house and turbine room are usually side by side on the same level, the multiple-deck arrangement being no longer adopted. Great importance is now attached to daylight illumination and to the satisfactory ventilation of the buildings, for these refinements have considerable bearing on the maintenance of maximum operating efficiency.

The mechanical handling and conveying of coal is carried out in various ways, depending upon the local conditions, the type of railway wagons available, and the internal and external storage arrangements. The machinery commonly employed includes various types of wagon tippers and rotary tipplers, together with telpher plant and conveyers. Several stations, more especially where some of the coal supplied is waterborne, make use of pneumatic plant, and such plant offers the advantage of greater flexibility and speed, but at considerably higher operating cost as compared with the methods in more general use.

The present-day power station requirements of greater evaporative capacity for a given floor space, and higher steam pressures, have decided the question of the type of steam-raising plant, namely, the water-tube boiler with its integral superheater; the marine type, steel-encased complete unit usually being employed in large stations.

It is beyond the scope of this address to refer to the various makes of boilers or to the many improvements in design and constructional details which have brought about, among other advantages, more effective water circulation and greater evaporation per square foot of heating surface. It is, however, of interest to note the great advance in size and output of the units now installed, due not to any probable gain in efficiency, as compared with smaller plant, but primarily to the necessity of reducing the size of the boiler house within reasonable measure of the turbine room. Even with the large boilers now being installed there is still a disparity in the ratio of approximately 1·75 to 1. Only a few years ago, boilers of 6 000 sq. ft. heating surface and 25 000 lb. evaporation per hour were considered large units, but these are small compared with units of 16 000 sq. ft. and 120 000 lb. actual evaporation, now in operation in this country. In America, boilers of 200 000 lb. evaporation per hour are becoming quite common.

The selection of the most suitable steam temperature is largely a question of the ultimate strength of the materials available, and according to expert opinion it is quite practicable to employ a total steam temperature of 750° F. Respecting the use of the higher steam pressures, there is considerable divergence of opinion as to the net advantage to be gained, for reference to the data of a number of the largest British and American central stations recently completed or approaching completion, goes to show that the adoption of the higher pressures is by no means general. Of 12 British stations referred to, one is working with a steam pressure of 475 lb. per sq. in., two have adopted 375 lb., two 320 lb., four 250 lb., and three 200 lb. per sq. in. The total steam temperatures range from 550° F. to 750° F. The engineers on the other side of the Atlantic are evidently more optimistic as to the superior possibilities of higher steam pressures, for of 12 American stations, two have decided upon a pressure

of 550 lb. per sq. in., three have adopted 400 lb., two 375 lb., one 350 lb., and five 300 lb. per sq. in. The steam temperatures range from 625° F. to 725° F. In two of the American stations some experimental plant at a pressure of 1 200 lb. per sq. in. is being installed, to work in conjunction with the main plant.

Turning now to the design of boiler furnaces, the improvement in connection with mechanical stokers has been very marked during the past few years, and, so far as the mechanism for feeding and distribution of coal and for the ejection of ashes is concerned, it is difficult to see where any further great improvement can be made. From the combustion and furnace efficiency point of view, however, there is still room for more satisfactory results, and the stoker is yet to be designed that will efficiently deal with all grades of coal, particularly the low-calorific-value slacks which many British stations are compelled to use. The results of experience with the coals available in this country have brought about the general adoption of the travelling chain-grate type of stoker which, for the satisfactory combustion of the lower grades of coal, are arranged for balanced draught with pressure-variation control at different portions of the grate. Unfortunately, with this type of stoker the furnace requires brickwork arches for complete combustion. These arches are a source of weakness and, as their span is limited by the rise of the crown, two or more of them have to be provided for in the furnaces of large boilers.

In American stations using, comparatively speaking, an unvarying quality of coal having a low percentage of ash and certain coking properties, the underfeed multiple-retort stoker is very popular, and this type offers the advantages of simplicity of furnace design, no arches, and fewer metal parts subjected to heat.

On the question of furnace efficiency, the adaptability of pulverized coal is receiving consideration, especially in America, where a number of trial plants have been installed, and are, from all accounts, giving good results. One of the objections to this method of firing is the necessity for providing the plant required for crushing, drying and pulverizing the coal, and the cost of operation. Apparently the latter item is not so serious as was at first thought with the latest plants installed, and is compensated for where the coals used have a high ash content. The likelihood of grit being emitted from the chimneys can be met by dust extractors. Amongst the advantages claimed for pulverized coal are: More accurate control of the fuel and air supply; thorough combustion of coal of widely varying grades, little ash to handle, and a negligible amount of combustible matter carried over; no smoke or soot troubles; reduced banking losses, and uniformly high efficiency. As to the economical efficiency of such plant, there are few actual figures available, but it is of interest to note that the makers guarantee efficiencies slightly better than those obtainable when firing the same quality of coal with mechanical stokers, working under similar conditions.

With modern high-capacity boilers, whatever method of firing is adopted, the upkeep of the brickwork setting is troublesome. The erosion of firebrick by molten ash, the leakage of air into the furnace, and the minimizing of heat radiation from the walls, are problems receiving attention. Furnace design in the future will probably be in the direction of dispensing with brickwork and surrounding the chamber by water-cooled surfaces. One of the features in the modern settings for large boilers is the height of the furnace. The advantage of this is that combustion is practically completed before the gases enter the tube nests, minimizing the amount of heat impinging on the lower tubes (so liable with forced draught) and also the amount of solid matter carried over into the flue. At the same time it is undesirable to increase the height of the furnace beyond certain limits, for radiant heat is a factor in furnace efficiency.

The advisability of utilizing, as far as possible, the heat contained in the waste gases passing to the main flue, and of increasing the radiant heat in the furnace, has led to the preheating of the air for combustion. The advantage of this has long been recognized, but until recently had not been applied in power station practice. Other methods of heating the boiler feed water are tending to displace water-heating economizers, and air heaters are now substituted or are used in conjunction with the latter. Further, the improvements in design and construction of mechanical stokers and boiler settings have minimized possible detrimental effects with air heated to about 350° F.

Another waste-heat refinement is the placing in the lower part of the furnace, where the ashes and clinkers are automatically dumped, of metal water tanks through which the feed water passes on its way to the feed heaters.

Efficient combustion is dependent upon the correct ratio of fuel to air, and therefore the advisability of having some means of accurately controlling the air supply has led to the introduction of several automatic regulating systems, but so far there is little information concerning their application.

The removal and disposal of the ash and clinker has all along been somewhat of a problem, and with present-day power stations it is a matter of importance almost equal to those of the coal and condensing-water supply. Dealing with large amounts of ash and clinker must obviously necessitate having in use the most suitable system for the specific conditions. Several stations have adopted the simplest arrangement possible, namely, large-capacity hoppers under each boiler, from which the ashes, in some cases crushed and quenched, are discharged into railway trucks, or as an alternative (where height of boiler basement is a consideration) into small steel wagons. In other stations the ashes and clinker fall from the hopper into a water trough, along which they are carried to a sump or ash-pit by a quantity of the circulating water discharged from the condensers, or by water circulating round the system. Other variations of this system are where the ashes and clinker fall into stationary water and are conveyed by a drag-link conveyer, or by water flushed through at intervals. Ash-handling by the coal conveyer arranged to return through the ash tunnel is no longer considered good practice. Suction ash plant, however, still finds some favour, notwithstanding its heavy

maintenance and operating costs as compared with those of the simpler systems. This system offers the advantages of cleanliness and flexibility for a congested lay-out.

The increased flue-gas temperature resulting from operating boilers at high pressures has brought economizers into favour again, for apparently maximum efficiency of plant cannot be obtained without their use, and many engineers express the opinion that the highest overall station efficiency lies in a compromise between feed-water heating by stage bleeding, and air and water-heating by utilizing the waste heat of the gases leaving the boilers.

The general adoption of higher pressures and temperatures has brought into greater prominence the question of feed-water purification; and the desirability of removing all scale-forming impurities, and also of taking steps to prevent any tendency towards priming and corrosive action, is universally admitted. This question concerns not only the steam-raising plant, but also the turbine and condenser. There are a number of well-known softening plants which render most waters suitable, as regards scale and the neutralization of free carbonic acid, for feed-water make-up, but many stations go further still by using evaporators, thus obtaining distilled water. The most perfect treatment of the water, however, may not prevent its causing corrosion, for the greater the purity of the water the greater is its tendency to absorb oxygen. Modern stations, therefore, employ a feed-water circuit closed as far as possible to prevent aeration from atmospheric contact, and in many cases, where very large boilers are installed, one or another of the de-gassing methods is also applied. For boiler-feed purposes, the steam turbine or electrically driven centrifugal pump, is now standard practice. The adoption of steam or electric drive is a question of station heat-balancing arrangements. Automatic regulation of the feed water to the boiler is very desirable, and there are reliable regulators on the market.

The higher the efficiency of the plant installed, the greater is the necessity for scientific supervision and control, and for the complete equipment of instruments for the attainment of the most economical results.

On account of the higher pressures and temperatures involved, the pressure-drop between boiler and turbine, the design of valves and fittings, and the arrangement of steam piping with special reference to the best means of dealing with expansion and contraction, are problems of much greater importance than in the past. The increase in pressure and capacity of the steam-raising units has certainly made for greater simplicity in the lay-out of the steam and feed piping.

Passing to the consideration of the turbine room equipment, considerable progress has been made during the past few years in the direction of increased efficiency and reliability of generating plant, and in improved steam-cycle conditions. The general growth of turbo-generators to the sizes now being installed has been considerable in a comparatively short period, and the development of the higher-speed machines has been still more rapid. The voltage and frequency adopted for generation tend more and more for general supply to become standardized at 6 600 volts, three-phase, 50 periods per second, and for this frequency the maximum speed is 3 000 r.p.m.

In the case of an isolated station, the maximum demand, the amount of plant available as stand-by, and, to some extent, the demand during light-load periods, are the important factors deciding the size of the set. With a base-load station feeding into an interconnected system, the problem is somewhat simpler. In this country the size of sets has so far been limited to 30 000 kW at 1 500 r.p.m., and to 20 000 kW at 3 000 r.p.m. The latter size will be the most economical yet produced, taking into consideration both capital cost per kilowatt and performance, for it is anticipated that the efficiency will be little lower than with a set of the same capacity operating at 1 500 r.p.m. It must be admitted, however, that the lower-speed set has the advantage of reduced stresses and therefore greater reliability. In America, where station capacities are much greater, there are sets up to 60 000 kW in use.

The continual tendency towards obtaining the maximum output at the maximum speed, combined with more stringent steam and vacuum conditions, i.e. the importance of increasing the heat-drop between the stop valve and the exhaust outlet, has brought about many changes in turbine design. Perhaps the most difficult problem in connection with greater output at increased speed and under high vacuum, is that of keeping the length of blades, blade speed and stresses, within reasonable limits, and at the same time reducing the leaving losses to a minimum. The methods most recently developed for obtaining increased leaving area are those known as the "duplicate exhaust" and the "multi-exhaust." The adoption of bleeding for feed-water heating reduces the quantity of heat rejected to the condenser, and consequently decreases the leaving losses to some extent.

The greater the temperature range the greater the possibility of casing trouble, due to distortion and steam leakage. In all probability the tendency will be more and more in the direction of the subdivision of the turbine into two cylinders, high-pressure and low-pressure, on one shaft. Such an arrangement also means some increase in efficiency, and, further, simplifies the system of reheating the steam before it passes to the low-pressure portion of the turbine. The higher the steam pressure, the greater is the necessity of adopting the reheating cycle.

Of the various other problems due to the changed and more severe conditions of working, those of the most suitable material for blading, and the precautions to be taken to prevent rapid deterioration, are of importance. Regarding corrosion, it is considered that the closed feed-water circuit and de-gassing system will prove beneficial. Further, most stations are now taking the precaution of preventing steam leakage into the turbine when standing. It is also usually the practice to leave the air pump in operation for some time after the turbine has been shut down.

The improvement in the design and construction of the steam end of the turbo-generator would not have been possible if corresponding advances had not been

made on the electrical side. Perhaps this statement should be put the other way round, for electrical designers maintain that the electrical portion has all along been a little in advance. Space does not permit more than a passing reference to improvements in the design and construction of large high-speed alternators. Although it cannot be said that the present design has reached perfection, considerable progress has been made in reducing mechanical and electrical weakness in such machines, and obtaining more efficient ventilation, particularly in the sets operating at 3 000 r.p.m., with the small diameter and long rotor construction. Reliability has also been increased by more effective methods of holding the rotor coils and stator end connections, giving greater ability to withstand short-circuit stresses.

Investigations as to the relation of temperature to the life of the insulating medium have given more confidence and a greater tendency towards the acceptance of machines designed to work at higher temperature limits, although there would appear to be need for caution with regard to some of the high temperatures proposed.

Notwithstanding the fact that water cooling, as compared with air cooling, means an increase in output, the former has made but little headway so far as the rotor is concerned, and still less in connection with the cooling of the stator. The method at present generally employed is to pass a continuous supply of fresh air through a "dry" or a "wet" type of filter to the alternator. Unfortunately, with the best of these filters the air will always contain some dirt, and a very small percentage in the large volume of air passing will mean a considerable weight of dirt carried into, and deposited on, the windings of the alternator. This serious shortcoming has resulted, therefore, in the development of the closed-circuit system of ventilation, in which the same air is used continuously and is cooled by being passed through a surface cooler. An advantage of this system is the minimizing of the fire hazard, in that the amount of oxygen in the air circulating would have little effect in maintaining combustion. The cooling effect is obtained by passing through the cooler a quantity of the condenser circulating water. There are cases, however, where the condensate is also passed through, and in this way some of the heat generated in the alternator is recovered for the feed water.

Condensing equipment has kept in step with the steam turbine development, otherwise the present-day economical results could not be attained. It is now possible to obtain surface condensing plant which will produce a vacuum so close to the theoretical limit that only in detail, and, possibly, in reduced operating power, can any further developments be looked for. Present-day practice in condenser design allows, as far as possible, for a uniformly effective cooling surface, a tube arrangement giving the minimum resistance to the vapour passing through, and limiting the heat transference to a comparatively low rate. This latter point is important, for with the cooling surface so designed there is some margin to meet such emergencies as a rise in the temperature of the circulating water, dirty tubes, or excessive air leakage into the condenser.

The necessity for maintaining a very high percentage vacuum, which means dealing with a correspondingly large volume of steam—for to obtain a slight increase in vacuum means a considerable increase in the volume of steam condensed—has rendered still more important the question of ample exhaust area, so as to ensure the resistance and vacuum drop between the turbine and condenser being reduced to a minimum. It is now the practice to connect the condenser direct to the turbine, that is, without an expansion piece, and to obtain the necessary flexibility by mounting the former on springs. When working at higher temperatures there is all the more necessity to provide for free expansion in the design and lay-out of the turbine and condensing plant.

The difficulty of obtaining continuous condensing service over long periods, and especially with dirty circulating water, has, in the case of large units, brought about the adoption of the duplicate set, or a single condenser so arranged that half the water side can be cleaned while the unit continues running under slightly reduced vacuum on the other half.

The usual method of controlling the supply of circulating water is by throttling on the delivery side of the pump, but the variable-speed motor, or the two-pump arrangement as adopted in some cases, gives advantage in the direction of economical operation.

Beyond adopting efficient screening plant and taking steps to prevent air leakage in delivery pipes to limit aeration, it is not practicable to improve the condition of the circulating water with the object of preventing corrosion of the tubes and other parts of the condensing plant. This trouble has long been a source of worry to makers and engineers alike, and, although a great deal of investigation and research work has been carried out, it cannot be said that we have travelled far towards a solution of this problem. Corrosion has in a number of cases been reduced by the application of electrolytic methods, but unfortunately the treatment found satisfactory in one case is of little use in another. Each case has to be treated independently; there are many variables, and time is the most important factor.

The power required, and therefore the cost of obtaining the highest vacuum possible under given conditions, is a serious matter, and with fractional-load stations it may be more economical to work with a somewhat lower vacuum; with a base-load station, however, the highest vacuum will mean the greatest economy.

Respecting condensing auxiliaries, the requirement of high vacuum has brought about many improvements in the apparatus used for extracting the air from the condensing system. Probably the most popular of these extractors is the multi-ejector, which, compared with other methods, offers the advantage of simplicity and also economy of working when the waste heat can be efficiently included in the station heat balance. Depending upon the condition of circulating water and feed-water supply, it is becoming the practice to duplicate the condensate and other pumps, usually having each set from 75 per cent to 100 per cent of full capacity. Practice also tends more and more towards the use of motor-driven auxiliaries, notwithstanding that many engineers consider steam-driven

auxiliaries to be more reliable. The electric drive has the advantages of lower first cost, more adaptability, and also greater economy, that is, when the waste heat from the steam drive cannot be fully utilized. Further, it may be considered to be equally reliable, particularly where motors are duplicated on the same drive and supplied with energy from different sources.

As regards the systems for auxiliary supply, house turbo-sets generating alternating- or direct-current energy, as the case may be, are now adopted in many stations, in some cases the whole of the auxiliary supply being obtained from two or more house sets. In other cases one set is in use in parallel with the main busbars through transformers, and so interconnected that in case of trouble on the main system the auxiliary supply is automatically thrown on to the house sets. This is a move in the direction of improved efficiency, but possibly at the sacrifice of some reliability. To obtain still greater efficiency, however, the tendency is to dispense with house sets and to take the supply from an auxiliary machine on the main generator shaft, with a stand-by supply through transformers or converting plant, as the case may be.

Power station apparatus for controlling large amounts of energy efficiently and safely is undergoing almost constant change in design, owing to the increasing capacity and voltage of the plant and equipment now employed. The more general interconnection of large stations is now a factor to be taken into account, for the switchgear is thus liable to be called upon to deal with short-circuit currents of enormous value, notwithstanding the limiting effect of reactors which in many cases are introduced between sections of the busbars and tie bars, and other points in the system.

The practice of direct connecting the generators to their step-up transformers, i.e. forming one unit, with control apparatus on the extra-high-voltage side, which may be at 33 000, 45 000 or even 66 000 volts, has brought about the most notable advance in switchgear design. In this country there are oil circuit-breakers now in use at 33 000 volts, for which is claimed a rupturing capacity up to 1½ million kVA, but this is, of course, an estimated figure only. In order to isolate the control apparatus to the greatest possible extent, it is now usual to separate the switch and transformer house from the main building. Such houses are of very considerable dimensions, for the space required for the gear to control energy at 33 000 volts is something appreciable, as, apart from the necessary spacing of busbars, etc., there must be accessibility to all parts for inspection and testing purposes, and ready withdrawal of oil switches and other details. Such gear is operated by electric remote control from some central position, by means of solenoid or motor, usually the former.

Whilst the majority of stations in this country have installed switchgear of the type relying for security against short-circuits by wide spacing of the live parts in air, and enclosed in stoneware or brickwork cubicles, the close-spaced enclosed compound-filled type of gear is finding considerable favour. This type has certainly, amongst its advantages, that of robustness and reduced space required, but the parts are not quite so accessible as with the cellular type of gear. Probably British engineers will continue to install the most reliable switchgear available, but there are many stations in America, and a number on the Continent, where the switchgear lay-out does not include cubicles, and the only safeguards are rails placed round each circuit unit. In this country we certainly go to the extreme limit, as regards special protection, to minimize danger to life and to secure continuity of supply. Of course, the Government regulations here are much more stringent than those in force in other countries.

Other developments in switchgear design include improved methods of mechanically or electrically interlocking the oil switches and circuit breakers with the isolating and selector switches, and of securing the latter against any possibility of being blown out. Improvements in the design and construction of current and potential transformers have given greater confidence in these details. It is now usual to include resistances in circuit with the latter to limit the current due to a fault. Modern practice does not include potential transformers in the main busbars, and small-ratio current transformers are not installed.

The previous remarks as to the fullest advantage being taken for the protection of switchgear in this country, also apply to the automatic isolation of faults in generators, transformers and feeders, for British practice makes full use of the various protective systems available. No doubt such practice will continue until some revolution in plant design dispenses with their necessity. In other countries practice leans to the opposite extreme, for in the majority of cases the protective devices are of the simplest kind. Several American undertakings are taking steps to ensure greater protection by such means, but owing to the size and complications of the systems the problem offers many difficulties. The necessity for electrically operating the switchgear has evolved supernumerary control, which automatically indicates the existing conditions of the system, as regards both the generating and the dispatching of energy.

In such an address as this it is impossible to refer in any detail to a subject of such magnitude as power station practice, but it is hoped that sufficient has been said to make clear the present trend of development. Before concluding, however, it may be of interest to make a few observations regarding present-day generating efficiencies, and those anticipated in the future, due to the application of higher steam pressures and heat-balance refinements. The results of power station efficiencies for 1922, recently published by the Electricity Commissioners, are somewhat disappointing, in that the maximum overall thermal efficiency does not reach 18 per cent and shows very little improvement on the maximum of the previous year. Further, the case for higher steam pressures is not helped by the fact that some of the best results are from stations working with comparatively low pressures and under no better load factor conditions. Thermal efficiency is not the only factor in economical generation; capital and maintenance costs are also of importance, but the returns certainly emphasize the necessity for making every

effort to obtain increased thermal efficiency as a net advantage.

The figures given by the Commissioners show that there are stations at present generating 1 kWh for 18 000 B.Th.U.'s of heat, and in America there are stations approaching completion where figures of 12 000 and even 12 000 B.Th.U.'s, equal to an overall efficiency of 24 per cent and 28½ per cent respectively, are mentioned, but to obtain the latter result some of the plant will be required to operate at a steam pressure of probably not less than 1 200 lb. per sq. in.

These results will not be obtained by increasing the pressure and temperature ranges only, but also by reducing existing heat losses and by improvements in other directions. For instance, the operating efficiency of large present-day boiler plant, including superheater and stoker-fired furnace, may be taken to be at least 80 per cent, with coal of approximately 10 500 B.Th.U.'s. It is maintained that an increase of 2 per cent can be obtained with pulverized-coal firing, under similar working conditions.

Turbo-generator steam consumptions have been reduced to 10 lb. per kWh, including the auxiliaries, and an efficiency ratio of 77 per cent, including the generator, can be obtained. Improvements now pending in turbine construction will, it is anticipated, lead to an increased efficiency ratio. Things are moving rapidly in these times, and we may realize sooner than expected the possibility of producing 1 kWh for, say, 1¼ lb. of inferior coal.

British engineers and manufacturers of plant will not be behind those of other countries in their endeavour to achieve the last word in economy, and so to cheapen the production of power as to place the industries of our Empire in a position to meet all competition in the markets of the world.

NORTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By Major H. Bell, Member.

(Abstract *of Address delivered at* Leeds, 13*th November*, 1923.)

At no period in the history of this Centre, in common with that of the Empire, have greater problems arisen than those which face us at the present time, and it is with the conviction that we, as a territorial unit of the parent Institution and members of an increasingly important section of the community, will play our part successfully and with advantage to others, that I look with equanimity upon the approaching session.

I feel I shall be voicing the thoughts of the whole of the membership of the Centre when I suggest that the events of the past month are such as to indicate that broad changes in fiscal policy are likely to take effect at no very distant date and, although fully realizing that within the precincts of the Institution is the last place in which anything in the nature of a political controversy should arise, I am tempted to offer a few observations on this subject in the hope that they will enable us to envisage more correctly any change which may come about and the more readily adapt ourselves to such change.

Previous to 1914, it was an oft-heard cry that the British electrical industry, then relatively small in point of capital invested, was stifled by reason of foreign competition, but in the ranks of our profession this belief was naturally not unanimous; I say "naturally" because the electrical industry, more than any other, embraces so wide a field of operation that whilst development is taking place in some of its branches, depression might easily exist in others.

Assuming that a change in fiscal policy is about to take place, we are justified in speculating as to its probable effect upon ourselves as a body, and I take it that I shall encounter few dissentients when I suggest that at any rate the immediate effect of any such change must be beneficial and that there will at once be a greatly increased demand within the Empire for British electrical manufactures. To supply these successfully it will be at once conceded that they must be the equal of, and in fact superior in every way to, those of all competitors.

The great war, however harmful its effect, certainly achieved one thing in that it stimulated in other countries, collaterally with our own, an intense scientific development in which electricity invariably figured in the vanguard, this stimulus being in some cases the result of dire necessity and in others of enhanced opportunity. Whatever the cause, however, it will be patent that if we are to achieve the superiority of which I have just spoken we must leave no stone unturned to ensure that we are in every sense equipped to meet these altered and more scientific conditions.

The burthen of my foregoing remarks may be briefly summed up by saying that in the future it will be doubly incumbent upon us, as an important branch of an Institution to which the peoples of this Empire are daily turning with increasing dependence and esteem, to apply ourselves with all our vigour and energy to those problems in connection with our internal economy which will tend to increase our sphere of utility, our efficiency, and the goodwill of others towards us.

As one of the principal factors in the attainment of these ideals, I should like to refer to the time-worn theme of the infusion of new blood into the Institution. After five years of hostilities, with their attendant partial disorganization of educational effort, and after a further five years of industrial dislocation, the steady influx into the Institution of the requisite number of adequately educated students has naturally been somewhat disturbed. It behoves us to ensure as far as possible that this state of affairs is remedied and that every entrant into the local ranks of the electrical profession, if his educational qualifications are appropriate, shall contemporaneously become a student of our parent Institution and an active participant at the meetings of this Centre. He will of necessity only develop into the latter if the suitable germinating influences in the shape of goodwill, sympathy and enthusiasm are apparent in the attitude of his older confrères. He must be encouraged to look upon the Institution as his Alma Mater to which he can at all times go for technical assistance and advancement, professional guidance and happy associations.

It is, of course, impossible materially to assess the advantages to be derived by an intending entrant from membership of the Institution. In order to achieve the highest ideal and the greatest degree of esprit de corps such material advantages should theoretically be nil and I think that, with regard to the infusion of new and suitable blood, broad success will come the more readily if both intending candidate and sponsor clearly envisage this desirable principle.

It is extremely gratifying to be able to state, by reason of the happy relationship existent between the North Midland Centre and the two Universities more immediately concerned—due largely to the co-operation and enthusiasm of the respective faculties—that the Students' Section of this Centre is to-day really "alive," but in view of the increased electrical developments which I have ventured to foreshadow earlier and which we have every right to expect, this is not of itself enough, and we must, by all legitimate means, contrive that the intellectual activities of the younger classes

are fostered to a degree which will ensure at all times a personnel adequate in every sense to meet the increased responsibilities which are destined to devolve upon the Institution.

Turning to a general review of electrical progress as more especially affecting this particular Centre, we are fortunately able to record that in spite of an unprecedentedly long and severe period of industrial depression, the electrical industry has escaped more lightly than is, generally speaking, the case in other trades. The reason for this is difficult to determine, unless possibly it is due to the fillip which has undoubtedly been given to domestic usage by reason of the greater standard of comfort now demanded by the public. The electrical industry is to-day so highly specialized that we each understand comparatively little of the others' pursuits and activities, but it is correct to say that the electricity supply industry may be looked upon as a barometer showing the condition of the trade generally.

It will be well within the minds of most of the members that specific and highly detailed information is now available in the shape of the Annual Report of the Electricity Commissioners, which report has been available for the past three years, and I make no apology for drawing your attention to several interesting facts revealed on perusal of the recently published Third Report.

One of the primary objects of the setting up of the Commission under the Electricity Acts of 1919 and 1922 was the formation of Central Authorities for the achievement of the cheaper production and more complete and penetrating distribution of electricity to all who desire to make use of it. The report in question brings to light the fact that such bodies have already been set up in 15 of the most important areas of the Kingdom. For the year under review 12 of these areas produced over half the total energy generated by public service corporations in the country, equivalent to approximately 3 000 million units. The total production of all undertakings for the year shows an increase of $17\frac{1}{2}$ per cent over the previous year.

It will be obvious that the reorganization of the various undertakings concerned, following upon the more precise delimitation of their areas of supply, has resulted in a largely increased installation of generating and ancillary plant amounting for the year to over 400 000 kilowatts, as compared with 170 000 kilowatts for the previous year, the total increase during the period since the setting up of the Commission amounting to the stupendous total of $1\frac{1}{4}$ million kilowatts. These additions, translated into monetary value, which of necessity is what more immediately concerns us, represent an expenditure of £26 000 000.

The foregoing figures are sufficient to demonstrate that the Electricity Acts of 1919 and 1922, although the subject of serious contention in their passage through Parliament, have resulted in very real and inestimable benefit to the electrical industry as a whole. Further perusal of the report shows that there are now existing in the country at least three public service plants producing over 200 million units annually, and six plants producing over half this figure.

My object in drawing attention to these few salient facts is to endeavour to show that Great Britain has "electrically" awakened and is now taking a place commensurate with her commercial greatness. It will be a matter of general interest and satisfaction to all that the efforts of the Commissioners have been successful in achieving an appreciably greater degree of standardization of voltage—the absence of which has hitherto done much to hamper and restrict the general development of the industry.

In passing, also, I am prompted to draw your attention to the steady but persistent increase in transmission pressures, a matter of paramount importance in connection with the cheap distribution of electricity. A pressure of 33 000 volts seems to have become recognized as a standard transmission voltage, no fewer than eight undertakings having carried out developments at this pressure during 1922–3, and it is further interesting to note that there already exists one underground system operating successfully at 66 000 volts.

With regard to the conservation of fuel, about which so much has been written since the closing stages of the war, it is gratifying to find that, due to a variety of causes, not the least of which has been the centralization of generation, there is a steady and persistent decrease in the amount of fuel required to produce a unit, corresponding to a drop of approximately 10 per cent for each of the past two years. The actual saving in this item last year over the preceding year amounted to more than £500 000. I have pleasure in drawing your attention to the fact that our Sub-Centre includes in its area two undertakings which conjointly figure as second in the national list of minimum fuel consumptions. In point of fuel economy, the British supply industry compares extremely favourably with its transatlantic neighbour, operating as the latter does on a scale of so much greater magnitude.

After careful consideration of the foregoing facts, taken in the aggregate I feel sure there will be little difference of opinion amongst us that in spite of the abnormal trade depression existent throughout the Kingdom, no matter what the cause, our industry has escaped in a large measure its ill effects.

I am somewhat loth, after the above remarks, to strike a minor key, but I should like to offer a few observations on the topic of electric street traction. It will, I know, be a matter for common regret that the development which has been so obvious and insistent in nearly all other branches of the industry has unfortunately passed by the door of the street tramway, and I suppose I shall not engender any dissent when I suggest that there is little difference between the electric tramcar of to-day and that of two decades ago. Contemporaneously with this dormancy other means of locomotion have improved at so phenomenal a rate that opinion to-day is very divided as to whether the tramcar, as we at present understand it, will not evanesce like its predecessors the horse tram and the steam tram, or be relegated to the comparative obscurity of our smaller provincial towns. Unfortunately, this is the treatment which has been already meted out to it to a considerable extent in the United States, and the growing disinclination of street authorities in this

country to give additional wayleave facilities would seem to indicate that similar defection may take place here.

Viewed in perspective, it would be difficult to diagnose the exact cause of the present unpopularity of the street car, but probably the absence of progression which I have previously indicated is the dominating influence, coupled also with the fact that traffic problems are now becoming so acute in even the smallest of towns that there is literally no room left for it. With commendable commercial spirit most of the large tramway undertakings have realized the inevitable and have availed themselves of the improvement which has taken place in other forms of locomotion, with the result that, though possibly the country is the gainer, yet the electrical industry and contemporaneously this Institution are, to some extent, the losers.

I cannot help feeling personally that there is probably a *via media* in this matter and that, given concentration of thought and new energy in its development, there is still ample possibility for improvement in the trolley car which would at any rate place it on a more equal footing, in point of speed and noiselessness, with its younger rivals. Another very interesting speculation in this connection is as to whether the present relative decline of the electric car may not bring in its wake very real advantages in the way of a more intimate association between the electrical and the automobile industries through the medium of the "electrobus" in one form or another, and I do not think that by any means the last word has been heard in connection with this type of vehicle.

In contradistinction to the lack of progress in street traction, the star of railway electrification appears to be in the ascendant, and signs are not wanting that not only is electricity to take its natural place in the operation of all of our denser suburban lines where, of course, its success is well assured, but that additionally in this proverbially conservative island of ours, main-line development is being planned and will be put into effect at no distant date.

Closely allied to locomotion is the problem of electric ship propulsion and it is rather a matter for regret to have to record the fact that, due to the extraordinarily depressed state of maritime transport, there has been, with certain few exceptions, little real progress in this country since the cessation of hostilities. The United States, on the other hand, due possibly to the encouragement derived from the construction of the "New Mexico" and her sister "dreadnoughts," has applied the experience gained thereby to a number of mercantile vessels. It is satisfactory to note, however, despite the tremendous activities of the United States Shipping Corporation during the war and the impetus which these naturally gave to marine design and progress in that country, that the last three electrically propelled vessels sailing under the American flag were built, engined and electrically equipped entirely in this country.

I feel that my remarks would be incomplete if before closing I made no allusion to the forthcoming British Empire Exhibition to be held at Wembley, commencing in the spring of 1924. There is evidence on every hand that the electrical industry is fully alive to the desirability of being represented in a manner befitting its present importance, nearly all sections being represented through one or other appropriate organizations. It only behoves us therefore individually to do all in our power by our presence and in all other possible ways to assist towards the success of this great effort admirably and opportunely conceived by the Mother Country and her Dominions.

Finally, in common with all my predecessors I ask your material support for the Benevolent Fund of the Institution. At no period of its existence has the fund been more inadequate than it is to-day to meet the very real necessities arising.

SCOTTISH CENTRE: CHAIRMAN'S ADDRESS

By R. B. MITCHELL, Member.

"THE ELECTRICITY SUPPLY BUSINESS AND ITS FUTURE."

(ABSTRACT *of Address delivered at* GLASGOW, 13*th November*, 1923.)

DEVELOPMENT.

The scope of this subject is so very wide that it is impossible to consider it in all its bearings at one meeting. To touch briefly upon some of the vast possibilities which lie before us in this sphere of industrial activity may be of interest.

It is, I think, realized by only a few that we in this country lag considerably behind America in so far as the uses of electricity are concerned. In Chicago, for instance, a state of development has been reached in which the demand is 700 units per head of the population. We in Glasgow have only attained to 130 units per head, and only very few undertakings in the country have gone beyond this figure.

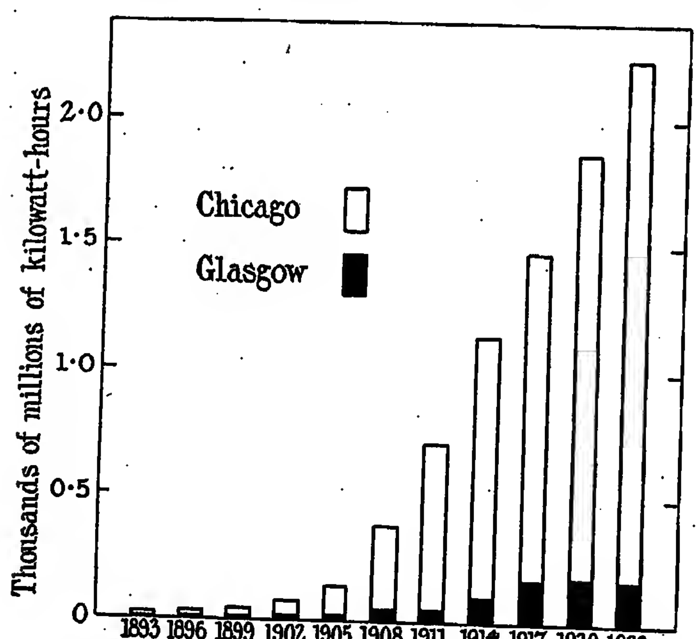

FIG. 1.—Comparative outputs of electricity.

It is interesting to trace the growth of the electricity supply in Chicago throughout the years, and compare it by means of curves with similar development in Glasgow (see Fig. 1). It will be noted that for a long period of years the line is on the horizontal, later on trending upwards to the enormous outputs of the present day. The curve for Glasgow shows very badly in comparison.

The possibilities before us in this country if we assume that the curve of development in this country will follow closely on the lines of those of the large cities on the other side, are boundless. During the past few years the tides of output and maximum load have ebbed and flowed in an unusual degree. In what may be termed the "boom" year of 1920–21, the tide may be said to have been at the flood after steady expansion at a rapid rate during the years of war. In the year following, came a rapid falling-off, and, in the current year, a turn for the better.

The curves of output and maximum demand in Glasgow during the years 1915–1923 (see Fig. 2) may, I think, be taken as typical of the experience of the majority of similar undertakings throughout the country. If the curves of output from month to month during the past four years are followed (see Fig. 3), the rise and fall and again the steady recovery will be seen in a more marked degree, in spite of the fact that trade is still very bad and unemployment general. It will be noted that for the first months of the present year, beginning on the 1st June, the output exceeds that of 1920–21, the boom year.

If the experience in Glasgow reflects that of other

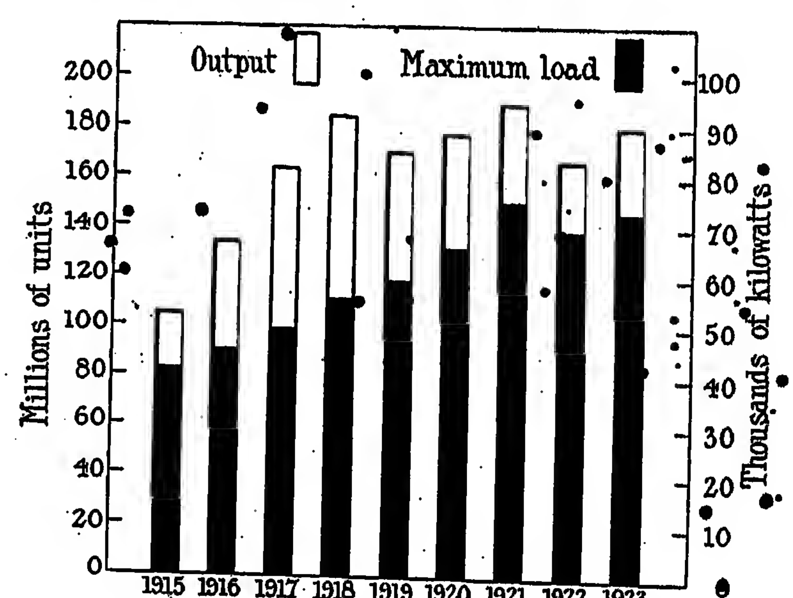

FIG. 2.—Annual output and maximum load.

undertakings, then those engaged in the business of electricity supply will require to set their houses in order, so that when this flowing tide sets in it may be adequately coped with.

GENERATING STATIONS.

The first thing which will naturally come up for attention will be the power station, and I propose now to review briefly the trend of present-day development. In this country, while such water power as exists bids fair to be utilized at no very distant date, the steam station must continue to bear by far the most important share of the load.

The division of the country into districts by the Electricity Commissioners, and the formation and work of controlling authorities in these districts, will slowly

but surely bring about the closing down of the small and uneconomical stations and the concentration of power generation in large stations well placed as regards fuel and water supplies. Generally it will be well worth while to equip these large stations with the most efficient plant obtainable. The load factors of these stations will be much better than those obtaining at the present day, and not initial cost but economy of operation—consistent with reliability—will be the first essential.

Nowadays electrical engineers engaged in the design and lay-out of new power stations or the extension of existing stations have to face problems more numerous and difficult than any ever encountered in the past. In the boiler room the problems presented are the

In the turbine room, the capacity and type of the turbine most suitable for local requirements; the electrical drive of the auxiliaries; the provision of duplicate or triplicate supplies from different sources for this auxiliary drive; the question of heat balance, which brings in the possible stage bleeding of turbines; the reheating of steam and the utilization of the heated air from generators, all call for serious consideration.

In the switch house, consideration has to be given to the question of switchgear to be adopted, whether of open or enclosed type, also the voltage of generation and transmission.

In the boiler house the trend is towards larger and larger units, and it looks as if we may arrive some day at the stage when one boiler only is installed per turbine

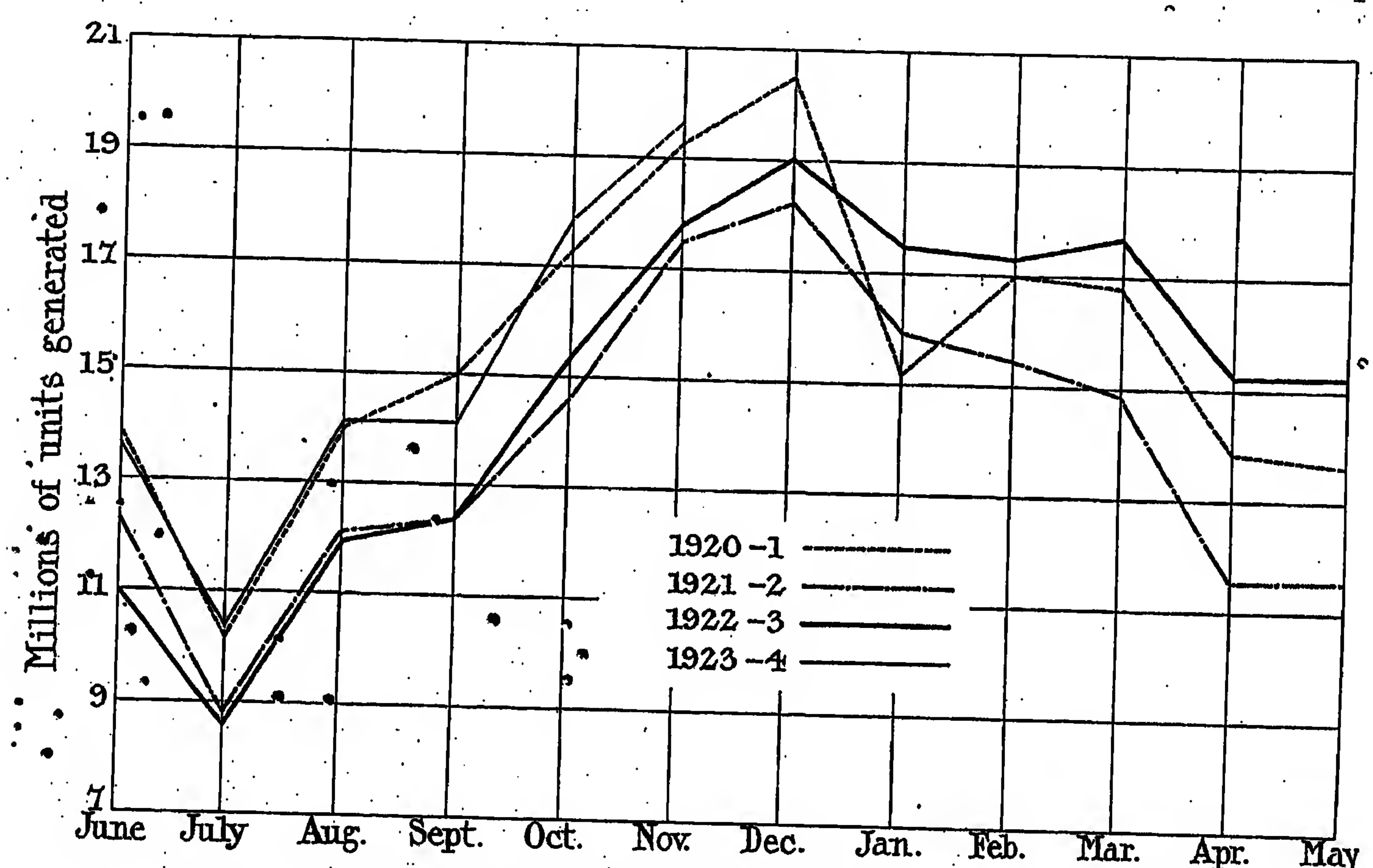

FIG. 3.—Glasgow Corporation Electricity Department: output comparisons.

high-pressure boiler and its combustion chamber, and the methods of firing (whether by coal on travelling grate or other stokers, or by pulverized fuel produced and burned in three or four different ways, or by gas firing, including the methods used for producing the gas). Then there is the system of ash removal to consider, whether by suction, by the simple direct method by means of wagons brought under the ash hoppers, or by one or other of the new hydraulic methods.

The utilization of every possible heat unit in the flue gases has also to be striven after, and here there is the possible use of either economizers or air-preheaters, or both. The feed pumps may be either steam-driven or electrically driven, or both types may be installed to be used as occasion requires for the maintenance of the heat balance. The feed water make-up, if obtained from a river or town supply, may require treatment to make it suitable for boiler-feed purposes or, as an alternative, the make-up may be evaporated.

unit instead of three or four as at present. This arrangement may have some advantages, but it has obvious disadvantages. My own view is that until load factors are very much higher than they are at the present day it is better to carry on with moderate-sized units.

Again, we hear of very high steam pressures being experimented with, a figure as high as 3 200 lb./sq. in. being mentioned. This very high pressure is chosen because at that figure no heat is absorbed in the change from water to steam. The pressure of the steam is reduced in passing from the boiler to 1 500 lb./sq. in., and passed into a high-pressure turbine, exhausting therefrom into another turbine of ordinary type at a pressure of 375 lb./sq. in. This development has not gone beyond the experimental stage, and no results are available. It marks a tremendous advance on present-day practice, but if put into use it does not appear to make for the ease of mind of central station engineers. Boiler makers anticipate no difficulty in

providing boilers for these high pressures, but the valves and boiler mountings generally present a real difficulty, and much development is required if these appliances are to be brought into line with other parts of the plant.

Increases in the efficiency of steam turbines may be looked for from increases, by stages, of pressures and temperatures to the highest figures possible. It has been stated that turbine designers anticipate no particular difficulty in designing machines for 1 200–1 500 lb. per sq. in. This is a subject of great interest to engineers at the present time. For these high-pressure machines two cylinders will undoubtedly be used, and in the high-pressure cylinders the parts will be small, with consequent safety.

With the increase in steam pressures and temperatures, it becomes more and more essential to use pure water for boiler make-up purposes. The present-day practice is strongly towards the provision of evaporators to ensure that the feed water is absolutely pure.

We may look forward to the operation of all large valves in power stations by hydraulic or electrical means.

While boilers are increasing in size, so are stokers. Until recently a boiler of, say, 50 000 lb. per hour capacity was provided with three stokers of the travelling-grate type. The provision of two stokers, or even one, for a boiler of this size is now considered to be quite good practice. We read of a single travelling-grate stoker, 24 ft. wide by 18 ft. 3 in. long, being supplied for a boiler in the Calumet station of the Commonwealth Edison Company, Chicago. It is stated that results from this stoker have been very gratifying, an overall efficiency of 81 per cent for the boiler unit having been obtained over long periods.

Gas-firing of Boilers.

The firing of boilers in power stations by low-grade gas, produced as a by-product from coke ovens or smokeless-fuel processes, is, I believe, limited only by the supply of gas available. There is a great need of smokeless fuel in large cities, the use of which would help in some measure to solve the ever-present smoke problem, at any rate so far as the domestic chimney is concerned. Glasgow, I am glad to say, is taking the lead in the consideration of this question, and a committee of the Corporation is at the present time going into the question of ways and means. The Electricity Committee has co-operated in agreeing to take such gas as is available from the process for boiler firing, at a price equivalent to the cost if ordinary coal were used direct.

A supply of gas from smokeless fuel or other processes, sufficient for the requirements of a large station, can hardly be expected. The extent of the plant which would be required for a station of, say, 100 000 kW capacity, which might consume in the ordinary way from 700 to 900 tons of coal per day, may be realized when it is kept in mind that the heat value of the gas is only one-fourth that of the coal from which it is produced. This is apart altogether from the question of the reliability of the supply. On a limited scale, however, the system is quite feasible, and I think it will be agreed that the firing of boilers by gas is an ideal method.

Powdered Fuel.

An alternative method of boiler firing which is now receiving more and more attention is that in which coal in powdered form is used, the powder, mixed with its proper proportion of air, being blown from nozzles into the combustion chamber. Here we have a method quite different from that of gas-firing in that it is applicable to stations of any size without materially increasing the space required.

The cost of installation of pulverizing plant is about equal to that of chain-grate stokers, but the cost of operation is necessarily greater. The question then is: Does the improved efficiency of combustion—the possibility of using lower-grade and cheaper fuel, the flexibility of operation of which is undoubted—of the pulverized fuel plant more than make up for the increased cost of operation and maintenance? It must not be forgotten that up-to-date stokers with well-designed combustion chambers will burn efficiently the lowest grades of fuel.

Efficiencies of Power Stations.

In the Annual Return issued recently by the Electricity Commissioners, it is interesting to note that the highest thermal efficiency obtained by any station in the country was 17·80 per cent, representing 19 163 B.Th.U.'s per unit delivered. This may be quite a creditable figure, but it can no doubt be greatly improved. The return will be of great benefit if it only serves to foster the spirit of emulation among engineers and staffs of stations in the various grades.

I think it is safe to predict that thermal efficiencies of 25 per cent will before long be obtained. This figure will be arrived at by the use of higher pressures and temperatures, preheating and bleeder feed-heating, and a close study of heat balance. A thermal efficiency of 25 per cent, representing 13 500 B.Th.U.'s per kWh, is predicted for the Weymouth station of the Edison Electric Company of Boston, U.S.A. The coal consumption in this case will be less than 1 lb. per kWh, since the calorific value of the fuel used is 14 400 B.Th.U.'s per lb.

Thermal efficiency is not everything; it is the total cost of the unit delivered at the consumers' terminals which is the real criterion. Reliability, capital charges, operating and maintenance costs, must be taken into account. The day may come when these factors will be included in the Commissioners' Reports, and the usefulness of the Reports thereby very much increased.

Air Preheaters.

It is essential nowadays to utilize fuel, on account of its cost and its value as a national asset, in the most efficient way possible. Consequently, with the view to securing the greatest economy, attention is being directed to stack temperature, and the possibility of recovering heat units from the gases entering the stack, which would otherwise be wasted.

I believe that air, preheated to a moderate degree before it enters the furnace, is a good thing, as there

will not only be the saving in heat, but also combustion will be improved and it will be possible to burn low-grade fuels efficiently. It is argued that an increase in the furnace temperature generally increases the rate of radiant heat transfer to all boiler surfaces exposed to the direct rays of the fire. If sufficient boiler surface is exposed, a greater proportion of the heat from the coal is absorbed as radiant heat with preheated air than is the case without preheating. Under such conditions, less heat remains to be absorbed by convection and the flue-gas temperatures are lowered. In other words, the total heat transfer will be increased, and the boiler efficiency will be further improved by the use of preheated air. In view of this argument it seems likely that air heaters, along with economizers, to ensure that stack temperatures will not be much above 300° F., will come into general use. The difficulties arising with brickwork, etc., in combustion chambers when air is preheated to a very high degree, say when economizers are dispensed with altogether, have not so far been overcome.

Dalmarnock Power Station : Comparison of two Methods (A and B) of Running Auxiliaries.

	Method A	Method B
Average load, kW	16 489	17 109
Steam pressure, lb./sq. in.	268	268
Steam temperature, ° F.	770	758
Vacuum at exhaust flange (bar. 30 in.), in. Hg.	29·076	29·145
Temperature at exhaust, ° F.	84	83
Condensate temperature :—		
At condenser, ° F.	55·5	55
At heater outlet, ° F.	99	123
Circulating water :—		
Inlet temperature, ° F.	49	49
Outlet temperature, ° F.	59	59
Total auxiliary consumption, kW	596	723
$\frac{\text{Aux. consumption} \times 100}{\text{Total output}}$, per cent	3·62	4·2
Steam per unit generated, turbine, lb.	9·91	9·9
Steam per unit generated, overall, lb.	10·55	10·77
Coal per unit generated, lb.	1·72	1·684
Heat units per unit generated, B.Th.U.'s	17 358	17 396
Coal per unit delivered, lb.	1·78	1·75
Heat units per unit delivered, B.Th.U.'s	17 964	18 077
Calorific value of coal, as fired, B.Th.U.'s	10 092	10 330
Boiler room efficiency, per cent	80·79	79·79
Turbine room efficiency, per cent	25·92	25·44
Overall efficiency :—		
Per unit generated, per cent	19·64	19·6
Per unit delivered, per cent	19·00	18·86

Conditions of test :—

A—With auxiliaries driven from a unit transformer connected directly to the alternator, the air pump being of the steam ejector type exhausting into feed heater. Electrical feed pump.

B—With auxiliaries driven from small house turbine exhausting into feed heater, the air pump being of the Leblanc type. Steam feed pump.

Power Station Auxiliaries.

At Dalmarnock, the turbine-room plant was modified in several directions so that experience could be obtained with the different systems of operation. One of the questions to be settled was the relative efficiencies of driving auxiliaries (1) by steam, and (2) by electricity. At Dalmarnock the auxiliaries have electric motor drive, and these can be supplied either from (i) house turbo-alternators exhausting into contact heaters, or (ii) (*a*) works transformers or (*b*) unit transformers on each alternator.

A series of tests was carried out recently to obtain information on this point, with interesting results. Turbine designers usually maintain that the house turbine method is the more efficient one. The test I am about to describe does not bear out this contention. The method of conducting the tests was to isolate one turbine unit and three boilers from the remainder of the station, and operate the turbine first with its auxiliaries driven from a unit transformer connected directly to the alternator, the air pump being of the steam ejector type exhausting into feed heater; and secondly, with the auxiliaries driven from a small house turbine exhausting into feed heater, the air pump being of the Leblanc type.

The two different systems are referred to as "A" and "B" in the table. In the first case an electrically

driven feed pump was used, while in the second a steam-driven pump was in operation for the boiler feed. It will be seen that the overall efficiencies obtained are practically identical in both cases, so that in this respect the use of the unit transformer scheme is thoroughly justified. The separate drive for the auxiliaries has, however, a great advantage during fault conditions or when the station is suddenly overloaded, as in these cases the speed of the auxiliary motors can readily be maintained, whereas with the unit transformer system the speed must fall with the drop in frequency of the main machines.

Safe Operation of Large Power Supply Systems.

The parallel operation of all plant is the ideal method from a standpoint of efficiency, and if automatic protective gear could be entirely depended on there would be no need to adopt any other system of operation. It is, however, impossible to avoid occasional short-circuits between phases, and when these occur the electrical and mechanical stresses are liable to cause serious failures of apparatus such as oil switches, and in this way bring about dislocation of the system. With complete interconnection the re-establishment of the supply after a serious fault is also difficult. The use of reactances to limit short-circuit currents has been widely spoken of, but the remedy is in all cases expensive and cumbersome, and in the case of 25-period systems hardly practicable. Experience in Glasgow has shown that with 60 000 kW on the busbars the substation oil switches are capable of rupturing the short-circuit currents produced. It has therefore been arranged that in this city, when the load on the system exceeds 60 000 kW, the busbars at the power station will be sectionalized, so as to keep the maximum short-circuit current within safe limits. In addition, the 6 000-volt distribution systems will be divided into definite networks each of approximately 20 000 kW capacity, the scheme being analogous to the feeder and distribution system which has proved so convenient in low-tension working.

Load Factor.

The improvement of load factor is all-important and supply engineers will be forced to take advantage of every opportunity of bringing this about. Conditions obtaining in post-war years have been all against the attainment of good load-factor figures. The discontinuance of night-shift working due to dull trade, the early closing of shops and the introduction of summer time, have all helped to reduce load factors. In my opinion, engineers must not be content simply to wait for better times but must attempt to stimulate the use of all appliances which will consume energy during the hours of light load. In dwelling houses this might be done by the heating of water during the night for use during the next day, and in business premises by heat storage at night in suitable appliances, also for use during the next day. Special low rates would be given for these supplies during restricted hours, and the only difficulty to be surmounted would be to ensure that the current would be used only within the restricted period. I believe that a great deal of business will be done in the future on these lines, and it will all help towards the lowering of the rates at which electricity can be sold.

Domestic Load.

The encouragement of the use of electricity in dwelling houses for purposes other than lighting, or in other words the development of the "domestic load," is another matter ripe for the serious consideration of the supply engineer. It is now being given the attention which it has all along thoroughly deserved. It should not need reiteration here that the domestic load is a desirable one, if only for its stability. It is much more stable than the industrial load which fluctuates with the state of trade. People have to cook their food and warm their houses irrespective of trade conditions. Not only cooking and heating but also water heating in bulk can be catered for. There is a very large business to be done in domestic water heating. Of course the rate of charge must be low, but I maintain that a very low rate can be quoted for this business and a profit obtained. I have always been a keen believer in the possibilities of the domestic load, and I consider that the time has now arrived when domestic load problems are well worthy of consideration not only by engineers in charge of undertakings but by the Institution as well. The Electrical Development Association is doing very valuable work in the encouragement of domestic propaganda, and is well worthy of the support now being extended to it by manufacturers, contractors and supply undertakings.

Domestic Supplies.

From an analysis of domestic consumers' accounts, it is apparent that the revenue from these consumers where lighting only is installed may be increased from five to six times by the introduction of cooking and heating appliances.

The old belief, formed some 20 to 25 years ago—that electricity is expensive and is only for the wealthy—dies hard. The selling staffs of supply undertakings are constantly having this objection raised by people who have little or no experience of the use of electricity. Even the consumer of some experience is slow in realizing that in using electricity for cooking and heating he is cutting out other expenses, e.g. for coal, gas, firewood, etc., which amount to a considerable sum when taken over a period of, say, 12 months, and he is very apt to grumble when the electricity accounts are rendered, even while fully appreciating the benefits of the electric service.

With regard to the rates of charge for domestic electricity, it is apparent that there is to be a general adoption of the two-part tariff, viz. a fixed charge based on the rental, floor area, cubic capacity or number of rooms in dwelling houses, and a running charge per unit used. To be attractive, the running charge should be fixed at the lowest possible limit, even at the expense of the fixed charge. Consumers naturally think in terms of the running charge, and the lower this is the more inclined they are to use electricity freely. It is only right that the two-part tariff should be offered

as an alternative to another tariff which should suit the small or the moderate user.

To my mind, a tariff for the small user should assess him at a certain number of units—equivalent to his lighting consumption—at the ordinary rates for lighting, and all units over this quantity at a much lower rate. New consumers would find this rate fair and equitable and they would gradually extend their use of electricity in the home to a greater and greater extent, until the day arrived when they would find it profitable to change to the two-part tariff. On both of these tariffs, one meter only is necessary. It is time that the duplication of meters in private houses, and in many other premises as well, should be abolished.

To develop this domestic load, it is necessary that every facility to use the supply should be placed in the way of the consumer. If he is unable or unwilling to purchase outright the heavier appliances, then these should be hired to him—at all events those appliances which are fairly large current-consumers; I refer more particularly to cookers and fires. From my own experience, I know that there is a great and ever-increasing demand for electric cooking and heating appliances on hire. It is rather astonishing that even in the case of fires, which can be purchased for very moderate sums, people for the most part prefer to hire. Probably the explanation is that if the hire charge includes the installation of the wiring and also the maintenance of the heating elements—as it ought to do—the consumer is relieved of a deal of worry and possible expense.

I do not consider that it is sufficient, having established suitable rates—and also, it may be, hiring schemes—to wait on business coming in. Propaganda without a suitable rate is useless, but, given this advantage, a reasonable propaganda will bring in business in a much more satisfactory way. In Glasgow recently, within the space of a fortnight at a demonstration of electric cooking and heating appliances held in one of the new housing areas, 166 fires and 38 cookers were hired to residents in that area. This was accomplished by means of a circular letter addressed to each house, inviting the people to come to see the demonstration. Later on, at a housing and health exhibition held in this city, orders for the hire of 258 fires and 52 cookers were received within three weeks. These results are, in my opinion, very satisfactory, and show what can be done by means of a little publicity.

Every opportunity should be taken to bring to the notice of the public the benefits to be obtained by the use of electricity in the home. In some large towns it may be necessary to go further than the hiring of appliances. In this city, for instance, there are 250 000 dwelling houses. Of this number only 14 000 have electric lighting installed, and the great majority of dwellings are not owned but only rented by the occupants. It seems to me that the only hopeful means of taking in this class of property is for the supply undertaking to inaugurate a scheme of wiring on hire or hire-purchase terms.

In municipal undertakings particularly, I believe that this suggestion might well be adopted.

It has already been stated by others that the domestic load is an "off-peak" load, and, on this account, very favourable rates can be quoted for domestic supplies. My own experience bears out this contention, and goes to show that the proportion of this load which comes on at peak time is very small, and may be put at from five to ten per cent of the connected load. In addition to this, the diversity of use is very high, and connections may be made freely within limits without fear of overloading distributors.

The factors applicable to the domestic load make it apparent that the capital charges—on the generating plant on account of its being mostly off-peak and on mains because of the high diversity factor—on units used must be very low, and therefore the undertaking can afford to charge low rates and still be sure of realizing a profit. It may be argued that in suburban districts the houses are sometimes widely apart, and to introduce the supply may be considered hopeless on account of the small return to be expected per yard of distributor laid. While this may have been so when lighting only had to be considered, I maintain that nowadays the situation has completely changed, due entirely to the possible other uses of electricity in the home. From a scrutiny of actual accounts it is clear that the "other uses" of electricity in dwelling houses increase the consumption in the majority of cases from 8 to 30 times and, as already stated, the revenue from 5 to 6 times that for lighting only.

Battery Vehicles.

The value of electric battery vehicles to power supply undertakings is not fully appreciated. The load is entirely an off-peak one and if even half of the horse transport work could be transferred to battery vehicles, it would represent an enormous amount of business. American supply undertakings have been much more progressive in this respect and at least 15 000 road battery vehicles are in operation in the United States. It should be noted that the electric battery vehicle is relatively much more expensive in America than in this country. In America one can obtain 12 Ford cars for the price of one electric vehicle, whereas in this country only 5 could be obtained. The Ford car is not generally accepted as a unit of currency, but it may serve to drive home the fact that the electric battery vehicle has made progress in America against even stronger opposition than it encounters here. In addition, the cost of petrol is much lower in America than in this country, while the cost of electricity is approximately the same. My own experience with good makes of battery vehicles has been very satisfactory and a life of 20 years (or say 200 000 miles) with very small repair charges should easily be attained. Batteries, too, are now greatly improved, but it seems to me that it really lies with the battery makers to decide whether or not the electric vehicle shall make real progress here.

Welfare.

I cannot conclude this address without referring in a few words to the subject of welfare in industry, a subject so closely affecting electricity supply undertakings. When the war broke out the cry was "munitions." Men, women, boys and girls, who had little or

no experience in mechanical operations, came from all parts of the country into the munition works which sprang up. Their physical, moral and spiritual welfare was of paramount importance. These mixed assemblages of people required the good influence of guides, especially when they were quite away from home influences. It was at this time that the Government did one of the wisest and greatest things of the whole war—they set in motion on a large scale a method which I hope is going to have an immense and lasting influence. Welfare schemes were organized for the special purpose of looking after the human side of these works. The actual results of this spirit of goodwill and fellowship were, I believe, astonishing. It was clearly demonstrated that work can be a pleasure, and also that this better feeling contributed to better work and a higher degree of efficiency. It brought all grades, including directors, managers, officials, foremen and workers, into closer touch and sympathy with each other. It dispelled many false views which kept men apart. It showed even that discipline can be exercised with goodwill. When men recognize that they are all operating for the common good, a spirit of self-sacrifice appears and glorifies all that is done. I speak with experience of actual operation of Whitley schemes, allied with welfare in the Glasgow Electricity Department.

It is now fully four years since, acting on instructions from the Corporation, a Whitley scheme was formed in the department to deal with what might be termed "domestic matters," and a welfare section, allied therewith, to deal with matters affecting the employees out of working hours. Sub-committees representative of trade and grade, each consisting of five members, the chairman representing the management, were formed in all sections of the department. These sub-committees send representatives to main committees, representing generation and distribution, the chairman of these committees being the superintendent of each section. Above these Committees again is a central committee, numbering 11, divided between management and employees. A welfare supervisor (part-time only) does the secretarial work of all committees.

This scheme, as already stated, has been in operation for four years and is an unqualified success. The men are now fully alive to the benefits which have been derived from the working of the scheme, and take a keen interest in the deliberations of the committees. A better feeling prevails all round, and I am convinced that the work of the department is being better done by a more contented body of men. All matters which cannot be settled in sub-committee are brought to a higher committee, and it is evidence of the good feeling prevailing when it can be said that the Central committee has not required to sit for over eight months.

For the success of a scheme of this kind, much depends on the tact and discretion of the welfare supervisor. One is astounded at the varied nature of the problems which this official has to handle, and in his capacity as a go-between between management and worker it is all-important that he should be the right man in the right place.

It may be argued that this subject has nothing to do with electricity, but we are, or should be, all interested in the humanizing of industry, and why not in electricity supply as in anything else. I recommend strongly, from my own experience, the establishment of such schemes as the one described, not only in electricity supply but in all other great industries throughout the country, and not from the materialistic point of view only, but from the humanitarian as well.

It is essential, I think, that an interest should be taken in the welfare of the worker, not only during his working hours but also in his leisure time. The employees should be encouraged and helped in the establishment of clubs for the carrying on of the various sports and recreations suitable for the time of the year and to the tastes and capacity of all classes and grades. The employees should be entrusted entirely with the carrying on of these clubs under general supervision.

Electricity supply is now vital to the prosperity of the country, and is rapidly assuming greater and greater proportions. It is essential that everything should be done to ensure its continuity. I am convinced that the proper carrying on of these schemes in electricity supply will go far to eliminate one of the factors which during the past few years have endangered this continuity to a serious extent.

DUNDEE SUB-CENTRE: CHAIRMAN'S ADDRESS

By J. C. Christie, Associate Member.

(Abstract *of Address delivered at* Dundee, 11*th October*, 1923.)

I propose to consider briefly the origin and the merits of some of the units of measurement in common use. This is a subject upon which it might be thought that the last word had long since been said, but a little consideration will show that it has been handled in an unscientific manner and is far from being so simple and perfect as it might be.

The first step towards a science of measurement was to learn to count, but our early ancestor found the purely abstract operation too much for his power of brain, so for a time he worked out his problems in concrete form with stones and twigs. Later he learned to cut notches on the twigs, and so came to make those marks which were the forerunners of our present numerals. Soon he began to feel the want of a counting machine ever ready by his side, and there, in the human hand, he found it. The hand was an instrument wonderfully adapted to those uses which had hitherto been required of it. It was the outcome of a long period of development, and survived as the fittest possible tool for grasping a stick or swinging from a branch. Unfortunately, this instrument was by no means equally suitable for its new purpose. It did fairly well until its owner got so far as ten; then, having no more fingers, a difficulty arose, and our early mathematician had to start again at one. It was therefore necessary to keep count of the number of complete tens; and so, in those far-off days, our notation was fixed upon a decimal basis. Here, at our very first step, we blundered badly. Certainly, had we chosen a scale of nine or of eleven in place of ten, things would have been worse; but, on the other hand, a scale based upon the number twelve would have been better, and, in my opinion, the scale of eight would have been the best of all.

To make a change now from the decimal scale is, I am afraid, impracticable. It would mean a period of confusion extending over a whole generation, and I fear that none who have passed school age would ever become thoroughly at home with a new multiplication table. All we can do then is to accept our notation as it stands, a decimal notation, and make the best of it. But we can never make the best of it so long as our various scales of measurement are not founded on the same base as our notation.

The great advantage of our Arabic notation over other systems is not that it is decimal, but that it is perfectly regular, and in the early days it was those nations who used this efficient tool who did good work in the science of numbers. Some progressive nations, like the Roman Empire, made little progress in this direction, the reason being clear if we try to multiply together the numbers MCIX and XLVII, using Roman numerals throughout. But before we condemn the Romans, let us remember that our British system of weights and measures bears exactly the same relation to the metric system that the Roman system of numerals bore to the decimal notation.

After the development of numerals came the introduction of units of measurement. In each case some convenient but quite arbitrary unit was first adopted, and naturally our ancestor concerned himself first with the simplest of all measures, that of length. Length being of one dimension only, is naturally one of the fundamental units, from which the units of two and three dimensions are derived. Any arbitrary length may be chosen as the unit, but the size which is most convenient depends upon the size of the things which are to be measured, and in general it is best to have a unit considerably smaller than the objects to be measured, so that fractions may be to some extent avoided. Thus to measure furniture we shall find the inch convenient. To measure houses we shall prefer to use the foot, while to measure counties we might use the mile. We see, therefore, that one unit is not enough. A range of units is required, and one would think that it was evident that a simple relationship between each step of the range was a great advantage. As our numerals follow a decimal scale, it would seem very simple to have our units follow the same scale, so that conversion from one unit to another could be effected without any calculation other than altering the position of the decimal point. This gives us a range in which each succeeding unit is ten times larger than the last, and for many purposes this works well. In some cases it is found that there is no need for such a close range of units, and then some of the intermediate steps can be omitted. We see an extreme example of this in the case of the measurement of electrical resistance, where we find the ohm a convenient unit, and then discover that the next larger unit required is one million times larger, namely the megohm. Sometimes it is the other way round, as in the case of our silver coins, where it is found that to have one unit ten times the size of the next gives too big a jump, and we then have to use intermediate units. This is where we notice the inconvenience of having a decimal notation. If we had a notation based upon a number on the binary scale, that is to say, if our notation were founded upon eight, which is a power of two, instead of upon ten, we could readily divide our unit by two, and these parts again by two, and so on without getting into awkward fractions. With the scale of ten this cannot be done, and I believe it is this more than anything else which prejudices the metric system and gives our British workman his

love for the inch, which is so conveniently divided into eighths. Here we have the weak point of the decimal system, but in spite of that I think that if our notation cannot be altered, then we should certainly make the best we can of it by converting all our scales to the same decimal base.

It still remains to find a fundamental unit with which to start, and man had found it so convenient to have his counting machine always by his side that he took his first units from the same source, and we find him measuring length by the foot, the pace, the forearm, the hand, the thumb, the span and other similar units derived from his own body. Thus, one of the earliest measures of length, that used by the Egyptians at the building of the Great Pyramid, was called the cubit, and is supposed to have been the distance from the elbow to the tip of the middle finger. Where great accuracy was not required, these units, based upon the size of the human body, were undoubtedly very convenient, and served well for a long period, and it is only in comparatively recent times that the necessity seems to have been felt for establishing standard units of greater accuracy.

In the reign of Edward II we find the English Parliament concerning itself with the matter, and in 1324 it was enacted that "The inch shall have the length of three barley corns, round and dry, laid end to end; twelve inches shall make one foot; and three feet one yard." It was not until the reign of Henry VII that the yard was chosen as our fundamental unit of length, and was fixed at something slightly under 36 inches of our scale. In 1834 a Commission was appointed, which sat for several years and finally produced the imperial yard. This was presented in the form of a bronze bar, 38 inches long by 1 inch square, near the ends of which two gold plugs were inserted and across these plugs fine lines were drawn. At 62° F. and 30 inches barometrical pressure, the distance between these two lines is one imperial yard, our standard of length.

For the introduction of a decimal system of measures our thanks are chiefly due to France. Towards the end of the 18th century it was suggested by Talleyrand that the Kings of France and England should appoint commissions to work together to determine the length of a pendulum swinging seconds. England did not respond to this invitation, but the French commission met and finally decided to adopt a standard of length derived from the size of the earth. It was intended to measure with care the length of the meridian of Paris from the North Pole to the Equator, and take one ten-millionth of this quadrant as the unit of length, to be called the metre or the measure. Actual measurement was begun of a part of this meridian extending from Dunkirk to Barcelona, but the fates as well as the British were against them, and the work was brought to a standstill by the Revolution. Some years later the work was completed, and a bar was made composed of 90 per cent platinum and 10 per cent iridium. It was made somewhat in the shape of an **H** beam, with the standard metre marked off along the neutral plane, so that the length would not be affected even should the bar deflect. That the determination of the metre has since been found to be somewhat inaccurate, and to be in fact more nearly true for the meridian of New York than for that of Paris, is a matter of no consequence, for to all intents the metre is just as much an arbitrary unit as the yard, and either would do equally well so far as its derivation is concerned.

In 1870 France again called an International Convention with a view to the universal adoption of the metric system, but again the fates were against her, for this time the matter was delayed by the Franco-Prussian War.

Whatever fundamental unit of length be adopted, the range to be measured is a wide one, from the smallest object known to man, the electron, on the one hand, to the vast spaces dealt with in astronomy on the other. For these varied measurements we have a wide range of units, with the Ångström unit, which is 10^{-8} cm at one end of the scale, and the light-year, which is 6×10^{12} miles, at the other.

As knowledge progressed, it was seen that there would be a great advantage in having some relation between the different units. Thus, if the yard be the unit of length, it is clear that the adoption of the square yard as the unit of area will simplify all calculations involving these two units.

It was also seen that the more complex physical units could be expressed in terms of a few of the more simple ones. Thus velocity, being an expression of the time taken to move through a distance, depends solely upon the units of time and length. Similarly it was seen that most of the physical units could be expressed in terms of the three fundamental units of space, mass and time. These were taken as the centimetre, the gramme and the second, and from their initial letters the name of the C.G.S. system of units was derived. This was the system which Lord Kelvin advocated in place of what he called "our absurd, ridiculous, time-wasting, brain-destroying British system of weights and measures."

When we measure a length we measure the whole of it, and to do otherwise would seem absurd, but when we measure certain physical quantities, we are in the habit of measuring, not the whole quantity, but merely the amount by which the quantity exceeds a certain minimum. That is to say, we measure from a false zero. This is how we ordinarily measure pressure and temperature, for example.

Pressure is commonly measured in at least three ways. We measure it in pounds per square inch from atmospheric pressure upwards. This is called "gauge pressure." We measure it in feet of water from atmospheric pressure upwards. This is called "head." And we measure it in inches of mercury from atmospheric pressure downwards. This is called "vacuum."

None of these methods of measurement is wholly satisfactory, especially as the atmospheric pressure from which we measure is itself a varying quantity, and these different ways of measuring the same thing have the effect of obscuring many otherwise clear problems in connection with condensing plant. For measuring boiler pressures there is perhaps something to be said for the present method, but even if we wish to measure from the pressure of the atmosphere, and not from the absolute or true zero, we should at least

decide what the unit is going to be, and stop using two of the three units now in common use.

The measurement of heat remained a puzzle for a long time, and this is not surprising seeing that it was only during the 19th century that men first began to understand its nature. It was obvious that more heat had to be put into 10 gallons of water than into one, when both volumes were raised to the same degree of warmth, therefore the apparent warmth or temperature of a body was no measure of the quantity of heat which it contained. Two distinct things had to be measured, the temperature and the quantity of heat. The temperature was the easier problem and was tackled first. Temperature is somewhat analogous to height, and in the case of a mountain tribe it might serve for most purposes if all heights were measured from some convenient point in the village, such as the level of the doorstep of the chief of the tribe, but the use of such a scale would not indicate any very high degree of intelligence on the part of the tribe. It would give the natives no true indication of the relative heights of the different parts of their country above sea-level, and all heights below the chief's doorstep would have to be reckoned as negative. In the case of height, even sea-level, though convenient, is only an arbitrary datum line; but in the case of temperature we have a true natural zero from which to measure, and yet we do not use it. Temperature was first measured indirectly by means of one of the effects of heat, such as the expansion of some substance, but there was no justification for assuming that this expansion was exactly proportional to the temperature, and indeed with some substances, such as water, this is far from being the case, although we now know that in the case of mercury the error at moderate temperatures is very slight.

Before we can measure temperature intelligently we must have a clear idea as to what it is that we are trying to measure. Every body is composed of a vast number of molecules, and, whatever the structure of their component atoms may be, these molecules as a whole remain motionless so long as the body is perfectly cold. Such a body is at the absolute zero of temperature. If the body be now slightly warmed, what happens is that kinetic energy from an outside source is imparted to the molecules, or in other words the molecules begin to move. In the case of a perfect gas these molecules dart about freely, but are continually colliding with each other and maintaining a rain of blows against the sides of the containing vessel. It is this effect which we call pressure, and in the gas thermometer, where the volume is kept constant, this pressure gives a true measure of the temperature by which all other thermometers must be calibrated.

In addition to the measurement of temperature, we have also to measure heat itself. For a time it was thought that this was something material, but it is now known to be simply energy in a special form, and may, therefore, be measured in the same units as any other form of energy.

This brings us to the most important of all the measurements made in a power station, the measurement of energy. The modern steam power station is simply a large machine for the conversion of energy from one form to another. It receives its raw material in the form of potential chemical energy, and its product is this same energy in a form more convenient for distribution and for use. The conversion is effected in a very roundabout way. First we take the chemical energy and convert it into heat energy, then convert this into mechanical energy, and lastly we convert the mechanical energy into electrical energy. We have thus three distinct processes going on in the power station, and these processes are carried out by the boiler, the turbine and the generator respectively. As we transform our energy three times, we have to deal with it in four different forms, chemical, thermal, mechanical and electrical, and in all these forms we must be able to measure it; but in each case we are measuring the same thing, namely energy, and there is no reason why we should not adopt the same unit of measurement in each case, merely using multiples or submultiples of this unit according to the size of the quantity to be measured. Unfortunately, when the problem was tackled long ago by the scientists of the early days, each worked in his own circumscribed department of science, and each introduced his own unit of measurement. Thus, the physicist measures energy in ergs. The chemist makes measurements as to the chemical energy stored in the coal, and he measures this in British thermal units. The mechanical engineer makes similar measurements, but, attacking the problem from a different point of view, he uses the foot-pound as his unit; while the electrical engineer uses a unit which he calls by the clumsy and ambiguous name of the Board of Trade Unit, or better, the kilowatt-hour, or better still the kelvin. The result of this is that we find energy measured by a weird and wonderful collection of units. We have ergs, joules, kilowatt-hours, calories, British thermal units, foot-pounds, horse-power-hours and kilogrammetres. The effect of having so many different units to measure the same thing is that results which should be obvious at a glance become hidden away behind names which bear no obvious or exact relation to one another, and simple comparisons are only made at some little trouble, and often are not made at all. Thus the engineer receives one ton of coal from the colliery, and he may know that its heat value is about 11 000 British thermal units per pound, but it is not obvious to him that what he has really taken delivery of is potential energy sufficient to raise the weight of the coal through a height of some 1 600 miles, or to raise a weight of 1 000 tons upwards of a mile and a half, or the equivalent of 7 216 Board of Trade units.

Let us now glance at the electrical units. These are all based upon the three fundamental units, the centimetre, the gramme and the second, and there is therefore a simple and definite relation between the electrical units, such as the coulomb, the ampere, the volt, the farad and the henry, and the other C.G.S. units, such as the joule and the watt.

The watt, for example, is not an electrical unit. It is simply a measure of power, and is in fact the C.G.S. unit of power multiplied by 10 000 000, but it is so simply connected with the electrical units that it is only necessary to multiply current by pressure, amperes

by volts, in order to express in watts the power in any electrical circuit where the power factor is unity.

The electrical units being based upon the fundamental units, electrical resistance is measured in terms of length and time, while the ampere and the volt are measured in terms of length, mass and time. Take the volt, for example. The fact that the volt can be expressed in terms of length, mass and time is by no means obvious, but let us consider how electrical pressure is produced. Electric pressure is generated in a conductor when that conductor is cutting magnetic lines of force, and the pressure produced depends solely upon the rate at which the magnetic lines are being cut; or in other words, the pressure depends upon three things, the length of the conductor, the speed at which the conductor moves, and the strength of the magnetic field through which it moves. Of these three things one is already expressed as a length; the second, which is a velocity, can be expressed as length divided by time; while the last, the magnetic field, can also be traced back to the fundamental units, for the strength of a magnetic field depends upon its distance from a magnetic pole of a certain strength. The strength of the magnetic pole is measured by the force with which it will repel another similar pole at a certain distance. A force is measured by the velocity which it produces in a certain mass in a certain time. If we now remember that a velocity is just length divided by time, we find we have reduced our definition of electrical pressure to terms comprising only length, mass and time. If we use the centimetre, the gramme and the second for our units, we arrive at a unit of pressure which is inconveniently small for practical use, and in actual practice we multiply this unit by one hundred million, and the resulting unit is familiar to us all under the name of the volt.

Unfortunately, our method of building up the electrical units upon the fundamental units of length, mass and time is not perfect. For one thing, it defines the strength of a magnetic pole by the mechanical force which it would exert upon another similar pole at a given distance. This definition fails to take into account the magnetic permeability of the medium in which the test is made, and further, it misses the important thing about a magnetic pole, which is not the mechanical force exerted by it upon another pole, but the strength of the magnetic flux proceeding from it. It is this fact which introduces the awkward factor 4π into so many electrical expressions.

The fate which befell the metre has also overtaken the electrical units. It has not been found possible to represent these theoretical units with sufficient accuracy for practical purposes, and in practice to-day our electrical units, like the unit of length, are represented by physical models. But although we know that the metre in use to-day is not any exact fraction of the size of the earth, but merely the distance between two marks on a metal bar which is kept in Paris; and although the ohm is not exactly one thousand million C.G.S. units of resistance, but merely the resistance of a certain column of mercury at a certain temperature; and although the ampere is not one-tenth of the C.G.S. unit of current, but merely that current which when passed through a solution of nitrate of silver under certain specified conditions deposits silver at a certain rate; there is nevertheless a scientific interest in comparing our units with some fixed quantity in Nature; if any such exist, and it would seem that there are certain such fixed natural units. One of these is the mass of the atom, say of hydrogen. Another is the wave-length of light at a given part of the spectrum; while another very minute measure of length which appears to be constant is the size of the electron, and it seems that here also we find Nature's own unit of electricity. In round figures, the number of electrons which equal one coulomb is 9×10^{18}. It is not suggested that our practical units should be changed to suit these natural units, but it seems possible that in the future our existing units may be defined in terms of them, so that they may be verified at any time.

There is no doubt that the rapid advance which has been made in electrical engineering is largely due to the exact system of international units which we possess, but many of our earlier and more common units are by no means equally simple and convenient. I think that the improvement of these is overdue, and I believe that the more the subject is considered and discussed, the sooner the improvement will be effected

WIRELESS SECTION: CHAIRMAN'S ADDRESS

By E. H. SHAUGHNESSY, O.B.E., Member.

(Address delivered 7th November, 1923.)

I desire first to say how much I appreciate, and to thank you for, the honour you have done me in electing me as your Chairman for this session. When this Wireless Section of the Institution was formed in 1919 after the war period of intensive development of radio telegraphy and telephony, there was so much matter ready for publication that the success of the first session was assured. It is a matter for satisfaction to know that the interest in the development of the radio art has been well maintained since the war and that the Wireless Section has been able to maintain full sessional programmes with well-attended meetings and do so much to foster that interest. I am glad to say that the prospects for an active session this year are quite satisfactory, and I should like to emphasize the fact that the meetings of the Wireless Section are open to all the members of the Institution.

I intend this evening briefly to review a few radio developments and then to give an account of some of the experiences met with in completing the Leafield high-power station.

BROADCASTING.

Perhaps the most striking development in radio work is that of broadcasting. The question of erecting broadcasting stations in this country was raised early last year when representatives of a large number of firms met at the General Post Office to discuss the subject. Many of these firms intimated their desire to erect stations, mostly in London. It was evident that rather than have a large number of stations of different powers and with programmes of different quality, with no definite guarantee of continued service for any period, it would be better if all the interests concerned would combine to produce a more workable arrangement. A scheme was produced which made it certain that purchasers of radio receiving apparatus would be given programmes for a period of at least two years from good stations of a standard power. The scheme provided for unified control of the stations and was put into operation 12 months ago. It is interesting to note that this country appears to have started its broadcasting under conditions which the directors of the Radio Corporation of America indicate in their annual report for 1923 as being essential for success.

What has been the result of this monopoly of broadcasting? The British Broadcasting Company have been able to collect an efficient staff of technical men and have had the advantage of, the assistance of, and co-operation with a large number of the radio and telephone experts in this country, and by a pooling agreement between the larger firms have been free from all troubles as regards the patent situation.

I remember that at the first meeting of the trade at the General Post Office, Mr. Dane Sinclair suggested that in order to reduce the heavy cost of running eight different programmes nightly the Post Office trunk lines should be hired, at any rate for partial simultaneous transmissions, but there were many of us who thought that the overhearing troubles, attenuation and distortion, would be too much to permit of any large degree of satisfactory simultaneous broadcasting of musical programmes. The Post Office engineers, however, have been able to select or make up such good trunk lines for this purpose that the engineers of the British Broadcasting Company have had every opportunity to exercise their skill and ingenuity.

I think that the quality of the broadcast music is a scientific development of no mean order, and that the successful simultaneous broadcasting may be said to have given this country the lead in that branch of the art. I feel confident that these results could not possibly have ben obtained in so short a time if the British broadcasting had been in the hands of several groups and different authorities.

Broadcasting should prove to the non-technical man that radio-telephony cannot supplant ordinary wire telephone exchanges, for by now he knows how easy it is to overhear speech and how very difficult it is, when comparatively near to a sending station, to get any speech but the one making the most noise.

Loud-speakers.—Twelve months ago there were very few loud-speakers which were either satisfactory or pleasant. So much attention has been given to this problem and its associated problem of well-designed low-frequency amplifiers using suitable valves, that to-day there is a much wider choice of satisfactory loud-speaking equipment.

Considerable incentive has been given to the manufacture of receiving valves, and a number of makers have successfully produced dull emitter valves consuming only a small amount of filament power. In 1913 Mr. Franklin showed me a valve working in the Marconi Company's station at Letterfrack and I then thought that valves would only be used by skilled electricians. To-day broadcasting has made valves almost as familiar in households as ordinary electric lamps. These things are good for the advancement of the art as well as for the trade.

Interference.—I fear that some interference with broadcast reception in areas near the coast is unavoidable, as the ship-and-shore service is essential. The report of the Broadcasting Committee ascribes much

of the interference due to ship-and-shore station spark sets to the indefiniteness of tuning of the wave-length authorized. We have recently carried out trials using a $1\frac{1}{2}$ kW spark transmitter in the General Post Office, London, adjusted to the correct wave-length and with as good a resonance curve as is obtainable for efficient range. Signals could be received on a valve receiver at North Foreland over a wave-band of from 470 m to 850 m. Arrangements were made with the Broadcasting Company to transmit a programme from Birmingham (420 m) whilst this test was taking place, and this programme could not be satisfactorily received at Dollis Hill, Ilford or Grove Park owing to the London spark interference. It was, however, possible to reduce considerably this interference by the use of rejector circuits.

Using the same aerial on the General Post Office and a tonic-train valve transmitter (800 note), the North Foreland station was able to read signals over a band of from 470 to 750 m, but the maximum signal tuning was sharper than with spark. The disturbance to the Birmingham reception on receivers not using reaction at the places mentioned above was about equal to the strength of the Birmingham signals. On using reaction on the receiver at Dollis Hill the strength of Birmingham was considerably increased without affecting the tonic-train disturbance.

The comparison of signal strength at North Foreland, using crystal reception, showed, however, that with 5 amperes in the Post Office sending aerial, signals were readable on spark transmission and were not audible with the same aerial current on tonic-train transmission. With tonic train using 8·5 aerial amperes the signals were just audible but dead weak at North Foreland. As most of the British and foreign ships are fitted with crystal receivers it will be seen that changing to tonic train with present power would considerably reduce the working ranges. Using valve reception at North Foreland the spark reception was only slightly stronger than the tonic train.

Radio Telephony.

An interesting demonstration of radio telephony was given early this year by the American Telegraph and Telephone Co., in conjunction with the Radio Corporation of America and the Western Electric Co. The time chosen for the demonstration was the most favourable period of the year, but it showed that conversation across the Atlantic could under these conditions be carried on by a system which employed less power and a narrower wave-band than would be required when using the ordinary methods of modulation. The other aspects of long-distance radio telephony remain unchanged.

Reception.—Apart from the Beverage antenna, of which I cannot speak from experience so far as reception is concerned, there seem to have been no recent improvements on the use of the well-known methods of high-frequency, selectivity, limiting and selective note tuning, and the employment of directive aerials which have been in use in this country for some years for long-distance reception.

Transmitting valves.—The life of transmitting valves is steadily improving. We have kept careful records of the lives of rectifying and oscillating valves actually in use at working stations, and the figures obtained may be of interest. At a station where 10 valves are in use, in 1921 18 valves were renewed after an average life of 450 hours, in 1922 five valves were renewed after an average life of about 1 000 hours, and up to the present time this year three valves have been renewed after an average life of over 3 000 hours, several of the valves now in operation having already run over 5 000 hours. At another station where 14 larger glass valves are in use they have been working for over 4 000 hours, and only one has been burnt out. The periods stated are, of course, actual working periods and do not include any idle time.

All these are glass valves of the General Electric Company's make, and the increased life is, I think, due to detailed improvement in manufacture and a better understanding of the management of the valves by the station operating staff. It is imperative that the valve filaments be run on a constant voltage if long life is to be obtained. I think that we have every reason to expect a life of from 6 000 to 8 000 hours from the valves now in use.

There has also been marked development in the power output of individual valves. Some of the Western Electric Company's anode water-cooled valves were installed at Northolt in July last and are still running. These are rated to give an output of 10 kW at 10 000 volts on the anode. We carried out an overload test on three of these valves at 12 500 volts on the anode for three hours and obtained an output of 42·5 kW in the aerial, or over 14 kW per valve. The anode of this valve is rated to dissipate 10 kW. With an output of 10 kW at 10 000 volts on the anode at 66 per cent efficiency it will be seen that there are satisfactory working factors of safety on both anode volts and dissipation.

The Holweck valve is another type of water-cooled valve. In this, all the parts are easily demountable and a working pump is permanently attached to the valve whilst it is in operation. An input of 10 kW at 5 000 volts on the anode has given an output of 8 kW oscillating energy. It has the advantage that a burnt-out filament can be renewed at a very low cost in a very short time. I understand that one of these valves has been working in the Eiffel Tower station for some time.

The Admiralty have successfully developed the silica valve, and valves with an output of 5 kW with 10 000 volts on the anode have for some time been made commercially by Mullard.

An Admiralty silica valve with an anode capable of dissipating 24 kW was exhibited before this Section last session by Mr. Morris Airey. This type of silica valve at 12 000 volts on the anode has an input of 33 kW and an output of 21 kW. The development by the Admiralty of silica valves of this and higher powers is proceeding. The filament of this type of valve can be renewed expeditiously at a small fraction of the cost of a new valve.

I think we should now rate valves on their output power anode volts and anode dissipation. With the

smaller power valves the permissible anode dissipation was a reasonable index of the permissible output, but with the larger power valves the permissible anode dissipation is no indication of the maximum output.

The Leafield High-power Station.

I shall now deal with some experiences we have had at the Leafield high-power station. A description of this station has already been published and I do not propose to cover that ground again. The station is equipped with 250-kW Elwell-Poulsen arcs. Some people thought that because the patents for the Poulsen arc had run out, arcs were necessarily antiquated, but the real development of the arc had taken place in quite recent years and the latest type exceeded in power and simplicity any other proved type of high-frequency generator. As a secondary consideration in the choice was the fact that the cost was reasonable, the patent monopoly having run out.

Leafield was the first high-power station to be erected in the middle of England, and as soon as it was operated reports of the large number and strengths of the harmonics and other undesirable emissions received from our friends caused us much perturbation. However, as the staff became more expert in adjusting the flow of methylated spirit into the arc chamber, the correct arc length and the correct field strength, these undesirable emissions were appreciably reduced, but it is still felt that every effort should be made practically to eliminate them. It was suggested that these harmonics, etc., were due to the type of antennæ used, and that the wave-lengths of some of the emissions would be related to lengths of sections of the aerial circuit. Others suggested that the insulated stay sections were the cause of trouble.

Quite apart from harmonics, another type of undesirable emission produces a general rushing, noisy disturbance in the neighbourhood of a wave-length far below the fundamental wave of the arc station. This disturbance is called "mush" and with Leafield working at about 9 000 m the mush appeared between 2 000 m and 3 000 m.

Radiation from the station.—In order to pursue these matters, systematic tests were carried out in 1921 at the Dollis Hill experimental station, situated 101 km from Leafield. Absolute measurements of the emission were made on both the fundamental and the two next immediate harmonics, whilst comparative values of the emission on the higher harmonics were obtained by observing and comparing, using a shunted telephone, the strength of received signals due to them. The specific objects of the experiments may be stated thus:—

(1) To obtain a comparison of the energies associated with the emission on the fundamental wave-length and on the harmonic wave-lengths.

(2) To observe the relative proportions of these energies for various power inputs to the emitting aerial.

(3) To obtain a value for the radiation height h of the Leafield aerial.

(4) To obtain information as to the cause of the harmonic emissions.

Observations on the fundamental wave-length were carried out using frame aerials, whilst those on the harmonics were made using a single wire aerial 100–110 ft. high and having a top run of about 150 ft.

The principle involved in the operation of making the measurements may be described as follows: (1) The signal from the emitting station is tuned in on the aerial, whether frame or straight wire, until the strength in the receiver is a maximum. A local oscillator, set to exactly the frequency of the emitted oscillation, is then arranged to induce into a dummy aerial circuit having characteristics equal to those of the aerial, and the strength of the oscillation observed in the same receiver. (2) The local oscillator is then adjusted until the signal received is of exactly the same intensity as that received from the emitting station. When this is the case the voltage induced into the dummy aerial circuit is equal to the voltage induced into the real and similar aerial circuit by the emitting station. From the value of this voltage, the known characteristics of the receiving aerial, the distance separating the receiving from the emitting station and the current in the emitting aerial, the radiation values required can be calculated.

The method of measurement follows that of Vallauri and Round and was described by Mr. Lunnon in 1921 in the discussion* on "Long-distance Wireless Transmission."

The local oscillator, embodying the method of measuring the voltage induced in the dummy aerial known as the slide-back method due to Captain Round, consisted of a carefully screened set purchased from the Marconi Company.

Experience has shown that it is not a difficult matter for a skilled experimenter to equate two sounds of equal intensity to within about 5 per cent when the note is pure. When one of the notes is impure, however, the error may be of the order of 20 per cent.

The radiation height of an aerial depends primarily upon the distribution of current in the vertical portion. This will very possibly be different in the two cases of fundamental and harmonic emission.

To overcome this difficulty the radiation height for the harmonic emissions has been assumed equal to the radiation height for the fundamental emission.

The value of h (radiation height) in Table 1 (A).—In evaluating the radiation height h in Table 1 (A) the value of I_s taken was that recorded in the transmitting aerial. This current, which, during the tests, was given values of between 100 and 190 amperes is, however, responsible not only for the emission on the fundamental, but also for the emission on the harmonics, and hence the value of I_s which should actually be used is equal to the recorded current minus the current necessary to produce the emission on the harmonics. From values obtained for the equivalent currents in the aerial to produce the second and third harmonic radiations, it can be conjectured that the total equivalent current to produce the whole of the harmonics is bounded by the value of 1·5 amperes. Hence the error involved due to this cause in the evaluation of h (the radiation height) may be taken as being of the order

* *Journal I.E.E.*, 1921, vol. 59, p. 677.

of 1 per cent, and within the limits of experimental error. For this latter reason no correction has been applied to the mean radiation height obtained from the results given in Table 1 (A).

The harmonic emission.—Every harmonic up to the 16th has been observed, and the characteristics of the second and third have been determined absolutely, whilst those of the fourth and fifth have been determined relatively [see Table 1, (B) and (C)]. The experiments show that, generally speaking, the field strength due to an harmonic decreases with increasing order of the harmonic, and that the strength decreases with decreasing aerial current to a greater extent than does the fundamental.

With 150 amperes in the aerial at Leafield, however, the emission of the harmonics is strengthened. This was observed on harmonics up to the fifth and confirmed on separate times and separate days. The harmonic emission is stronger than when there was 177 amperes in the aerial, and a noticeable factor with this aerial current of 150 amperes was the comparative purity of the notes in the harmonics. The note obtained on the harmonics at all other currents was complex, and indicated that the emission was more in the nature of damped wave trains than that of pure continuous waves. This is presumed to be due to variable cycle-to-cycle characteristics of the arc and that at 150 amperes in the aerial the arc maintains a steadier characteristic with consequent purified wave-form and stronger harmonics. If this were the case it would also be reasonable to assume that the fundamental emission at 150 amperes would be improved [Table 1 (A)]. The tests do not show that this is materially the case. Such an effect might, however, be noticed at a more distant station.

Cause of the harmonics.—It is thought that the harmonic emissions are entirely due to the operation of the arc and not to radiation from stay wires or harmonic oscillation of the aerial.

Table 1, (B) and (C), and Table 2 show that the potential gradient, the square of which is proportional to radiated energy, decreases roughly in the ratio of 2 : 3 for each harmonic.

The harmonics are true harmonics inasmuch as their wave-lengths are (within the limits of the wave-meter used) true integral fractions of the fundamental wave-length. The facts that every harmonic is received, that they are true integral fractions of the fundamental, and that their strength is apparently independent of the possible normal modes of oscillation of the aerial, all indicate that the aerial itself does not oscillate harmonically, but that the emissions are due to forced oscillations set up in the aerial by the operation of the arc.

All the measurements were taken on a wave-length of 9 050 m, and the mean value obtained for the radiation height of Leafield was 72·5 m.

The individual values obtained by using different aerial currents of values between 127 amperes and 191 amperes did not differ from the mean value by more than 3 per cent. The height of the masts at Leafield is about 92 m.

By changing the fundamental wave-length to other values such as 8 750 m and 12 300 m and observing the wave-length values of the harmonics produced, it has been confirmed that these are produced by the operation of the arc.

Tables 1 and 2 give the values of the sending aerial current and the values of the potential gradient in microvolts per metre at Dollis Hill, and the values of the radiation height, radiation resistance and radiated energy deduced therefrom.

The results obtained are very interesting. With an aerial current of 191 amperes (representing an aerial energy of about 80 kW) on 9 050 m it is calculated that 3·95 kW are radiated. With the same condition the radiated energy on the second harmonic (4 525 m) is 0·000194 kW. With 176 aerial amperes on the third harmonic (3 016 m) the radiated energy is 0·00005 kW. It will thus be seen that the energy wasted in harmonic radiation from Leafield is a negligible percentage of the total radiation. It is, however, important to know that such a small amount of radiated power can cause interference. It has been suggested that the permissible undesirable emission from a transmitting station shall be a percentage of the power of the station, in the future a fixed maximum amount may have to be decided upon for the largest stations.

To investigate methods of reducing harmonic emissions, experiments were carried out at Stonehaven, where the aerial is supported on 250-ft. masts and where a 24-kW Admiralty Poulsen arc had been installed and where plant was available for building a coupled circuit. No reliable results could be obtained close up to the station as appreciable harmonic radiation was obtained from the primary circuit, the aerial being disconnected. A receiving station was erected at Aberdeen (about 16 miles from Stonehaven) and comparative tests were made using direct aerial and coupled-circuit working. With the direct aerial circuit the harmonics were pronounced and no difference was observed in their strength at Aberdeen whether either the marking and spacing wave method of working or the marking wave with silent spacing interval method of working was used.

When the primary of the coupled circuit was energized with the aerial and secondary circuit, disconnected weak fundamental signals but no harmonics were received at Aberdeen, the radiation being from the primary tuning coil in the Stonehaven station. When the coupled circuit was joined up to the aerial the harmonics were very distinctly reduced.

The "mush" with a plain aerial produced a disturbance at Aberdeen sufficient to swamp out very weak signals, but with the coupled circuits the mush was reduced to such a small amount that not even weak signals were disturbed.

It may be interesting to observe that with the direct aerial working, an input of 15 kW to the arc produced an aerial current of 39 amperes, and with the coupled circuit an input of 19 kW was required to produce the same aerial current of 39 amperes, the current in the primary circuit being 33 amperes.

Although experience has shown that it is not safe to assume that results obtained on small powers can be reproduced with facility on larger powers, these

TABLE 1.

Values of ϵ, H, h_s, R_r and Radiated Energy for Various Values of Aerial Current (I_s) at Leafield.

(A) Fundamental wave-length = 9 050 m.

I_s	E	ϵ	H, in C.G.S. units	h	R_r	Radiated energy
amps.	μV	μV/m		m	ohm	kW
191	153·2	5 580	186 × 10^{-9}	72·9	0·104	3·95
175	139	5 080	169 × 10^{-9}	70·5	0·097	2·97
150	124·8	4 560	152 × 10^{-9}	73·7	0·106	2·38
127	104	3 810	127 × 10^{-9}	72·9	0·104	1·62
102	72·6	2 650	88 × 10^{-9}	63·5	0·079	0·82

Neglecting reading at 102 amperes :—
Mean value of radiation height = 72·5 m
Mean value of radiation resistance = 0·103 ohm

(B) Second harmonic = 4 525 m.

I_s*	E*	ϵ	H, in C.G.S. units	h	i_r	R_r	Radiated energy
amps.	μV	μV/m		m	amp.	ohm	watt
197	754	41·2	1·37 × 10^{-9}	72·5	0·687	0·412	0·194
177	566	30·9	1·03 × 10^{-9}	72·5	0·516	0·412	0·11
150	695	37·9	1·26 × 10^{-9}	72·5	0·634	0·412	0·165
126	500	27·3	0·91 × 10^{-9}	72·5	0·456	0·412	0·086
101	277	15·1	0·5 × 10^{-9}	72·5	0·252	0·412	0·026

* Mean values of I_s and E are taken from Table 1 (A).

(C) Third harmonic = 3 016 m.

I_s	E	ϵ	H, in C.G.S. units	h	i_r	R_r	Radiated energy
amps.	μV	μV/m		m	amp.	ohm	watt
176	382	20·9	0·7 × 10^{-9}	72·5	0·232	0·927	0·05
150	484	26·4	0·88 × 10^{-9}	72·5	0·294	0·927	0·08
127	281	15·3	0·51 × 10^{-9}	72·5	0·170	0·927	0·027
102	125	6·83	0·2 × 10^{-9}	72·5	0·076	0·927	0·0054

TABLE 2.

Comparison of Potential Gradients (in μV/m) at Dollis Hill, due to Emission from Leafield.

Aerial current	Potential gradient, in μV/m				
	Fundamental	2nd harm.	3rd harm.	4th harm.*	5th harm.*
amps.					
191	5 580	41·2	—	21	26
177	5 080	30·9	20·9	15	13
150	4 560	37·9	26·4	26	21
126	3 810	27·3	15·3	10	7
101	2 650	15·1	6·8	4·5	—

* Values in these columns are interpolated from shunted telephone results.

results were considered sufficiently promising to justify further trials on a larger scale at the Northolt radio station where a larger arc had been installed and where the aerial is supported on 450-ft. masts. Both the mush and the harmonics from this station had proved disturbing to some communications near London.

In building up the coupled circuit here and finding the best values for inductance capacity and coupling, the primary condenser insulation was broken down on two or three occasions and plain aerial working was resorted to, with the result that on each occasion immediate advice of creating disturbance was received. Both mica-insulated and oil-insulated condensers were tried at Northolt, but the losses in the mica condenser were found to be much less than those in the oil condenser, probably owing to the oil being damp and dirty.

The new aerial tuning inductance proved to be of higher resistance than was expected. With direct aerial working an input of 28 kW to the arc produced an aerial current of 46 amperes, and with the coupled circuit an input of 35 kW to the arc produced the same aerial current of 46 amperes, the current in the primary circuit being 39 amperes.

Observations at Dollis Hill (about 7 miles from Northolt) show that with a coupled circuit working the harmonics were practically eliminated and the mush reduced to a negligible quantity. With direct aerial the receiving telephone had to be shunted with 20 ohms to get rid of the second harmonic, and with 120 ohms to get rid of the third harmonic.

With coupled circuit using an extra valve on the receiver on most occasions no harmonics were observable. On a few occasions when they were traced a shunt of over 1 000 ohms on the telephones caused them to disappear.

The mush when a plain aerial was being used prevented the signals from North Foreland from being properly heard at Dollis Hill, but when the coupled circuit was in use no difficulty whatever was experienced.

The wave-length of Northolt is about 7 000 m and the coupled circuit has been installed permanently for about 12 months. The Dubilier mica condenser in the primary circuit is subjected under working conditions to 30 000 volts at a frequency of about 40 000 p.p.s. and has behaved satisfactorily. These results have encouraged us to proceed with a coupled circuit for Leafield where the power and voltages to be dealt with are of a greater order, but the work is not yet completed.

In connection with the reduction of harmonics and mush, Pederson published a description of some experiments with a cooling shoe placed upon the top of the carbon electrode and capable of adjustment from a distance. The idea was that with proper adjustment the arc would rise between the electrodes, strike the cold surface of the shoe and be instantly extinguished. The copper anode is already water-cooled at the tip. The result would be to make every cycle of the arc exactly similar and reduce undesirable emissions. We have tried an experimental cooling shoe on the large arcs at Leafield, but have not yet been able to form any definite opinion of the effect. Several types of shoe tip have been tried but, owing to the intense heat of the carbon, on each occasion the tip has melted after about half an hour's working. Coating the Leafield carbons with a thin layer of insulating material seems to produce a slight diminution of the mush.

It might be concluded from these remarks that a large arc is a very disturbing element, but that is not the case. The receiving station associated with Leafield is at Banbury (20 miles away) and reception of Cairo and weaker stations is carried out there whilst Leafield is working on full power.

An experiment was carried out to determine whether satisfactory reception nearer to Leafield could be undertaken. A frame aerial pointing towards Leafield on the Leafield–Cairo line was erected 10 miles from Leafield. Cairo on 11 000 m and Marion on 11 600 m were read without any difficulty whilst Leafield was working on 12 300 m.

Neither must it be concluded that valve oscillators are free from harmonics. I hear a well-defined continuous-wave tonic-train valve station sending out groups of figures nightly. I get these signals with about six distinct maxima when swinging the condenser through a range of from 300 to 800 m at a receiving station which is, I believe, about 7 miles from this transmitting station. This is not a Post Office station.

It was stated in the Imperial Wireless Telegraphy Committee's Report of 1920 that 1 aerial ampere produced by a valve oscillator is equal to $1\frac{1}{2}$ aerial amperes produced by an arc. After the installation of a valve transmitter at Stonehaven a direct comparison was made. The arc set and the valve set were in turn connected to the same aerial and adjusted to produce 47·5 amperes at 4 800 m. The potential gradient measured at Dollis Hill was 63·6 μV/m for the arc and 62·5 μV/m for the valve. So far as experimental measurements of this nature are concerned, the potential gradients may be said to be equal. Berlin reported that the signal strengths from the two sets were approximately equal but that there was more variation with the arc. It must be emphasized that to get these equal results it is necessary to have the arc clean and in very good adjustment.

Insulation troubles.—When Leafield was put in operation it was found that if the aerial current was increased above 190 amperes the insulators on the mast stays brushed over. These insulators were carefully watched and when some of them were removed they practically crumbled in the hand. An inspection of the broken parts indicated that they had been subjected to intense internal heat. With arc working the aerial current is on continuously during the spacing interval as well as during marking, and the stay insulators get no rest from dielectric stresses and no chance of cooling down. Larger insulators and then two separate insulators in series were tried at each point, but after a period of working the trouble reappeared. It will be appreciated that the crumbling of stay insulators may result in the collapse of a mast during a gale.

It was not found possible to get a satisfactory insulation of the stays which would permit of a larger aerial current than 190 amperes being used in all conditions of weather. It was therefore decided to short-circuit the insulators in all the top stays of the masts and at the same time bond the stays to the mast

at their top ends, well earthing the bottom ends. The change was made gradually as no work could be done on the stays whilst the station was working. This operation took from June to September, 1922, and systematic radiation measurements were made at Dollis Hill on 8 750 m and 12 300 m as the work progressed. The mean results of the tests when the work was completed gave a radiation height of 76 m for a wave-length of 8 750 m, and a radiation height of 74 m for one of 12 300 m. Allowing for errors of observation, these results compare satisfactorily with the value of 72·5 m radiation height obtained before the change was made. From this we conclude that the radiation from Leafield has not been affected to any measurable extent by the cutting out of stay insulators. The result of the experiment has, however, allowed the normal working aerial current at Leafield to be increased from 190 amperes to 250 amperes without any fear of trouble from broken insulators. The insulators supporting the aerial have given us no trouble.

The aerial tuning inductance is 12 ft. in diameter and is supported on columns of hollow porcelain reels. In order to make them rigid, paxolin tubes were passed through their centres, hooked to the bottom support and clamped tightly at the top. After a period of working these caught fire and the porcelain was punctured. Dry wood was then tried but with no better result, and finally a wooden spider placed at the top of the tuning coils held the columns together and this has stood the test of time.

Recently during some building alterations to the aerial tuning inductance room a temporary wooden partition about 8 ft. from the coil became damp during a storm and shortly afterwards caught fire as the result of being in the field of the high-frequency currents. The builders had been warned to keep it dry but were of the opinion that the warning sounded like a fairy tale. The fear of any further trouble was overcome by erecting a screen of about 12 copper wires between the coil and the wooden partition.

INSTITUTION NOTES.

Local Centre in China.

The Council have sanctioned the formation of a Local Centre in China, with headquarters at Shanghai.

Associate Membership Examination Results: August 1923.

ROYAL CORPS OF SIGNALS.

Passed in "The Theory of Electrical Military Signalling."

Akehurst, Lieutenant C. H. (23rd Sikh Pioneers, I.A.).
Burt, Lieutenant G. M. B. (1st Bn. 12th F.F. Regt., I.A.).
Collin, Captain E. P. C. (18th Lancers, I. A.).
Dent, Lieutenant W. H. N. (Northumberland Fusiliers).
Gem, Lieutenant R. H. (The Buffs).
Harris, Captain J. N. A. (69th Punjabis, I.A.).
Hinds, Lieutenant C. D. (R.G.A.).
Hurst, Captain G. S. (4th D.C.O. Hodson's Horse, I.A.).
Jourdain, Lieutenant F. W. S. (Oxf. and Bucks. Lt. Infantry).
Leonard, Captain R. G. (5th Gurkha Rifles, I.A.).
McGregor, Lieutenant W. D. [1st (K.G.O.) Gurkha Rifles, I.A.].
MacMillan, Captain D. MacL. (3rd R. Bn. 3rd Sikh Pioneers, I.A.).
O'Sullivan, Lieutenant P. R. (Wilts. Regt.).
Palmer, Lieutenant W. J. (R.F.A.).
Ridley-Thompson, Lieutenant E. L. (The Queen's Bays).
Sugrue, Lieutenant W. F. (Beds. and Herts. Regt.).
Thompson, Lieutenant T. C. (The Royal Fusiliers).

The Physical Society of London and the Optical Society: Annual Exhibition of Scientific Apparatus.

Tickets of admission to the above Exhibition, which is to be held at the Imperial College of Science, South Kensington, on Wednesday and Thursday, 2nd and 3rd January, 1924, can be obtained from the Secretary of the Institution.

Committees, 1923-1924.

Among the Committees appointed by the Council for 1923–24 are the following:—

INFORMAL MEETINGS COMMITTEE.

The President.

Mr. J. R. Bedford.
Mr. J. Coxon.
Mr. P. Dunsheath, O.B.E.
Mr. R. Grierson.
Mr. A. F. Harmer.
Mr. E. F. Hetherington.
Mr. A. G. Hilling.
Mr. F. Pooley.
Mr. W. E. Warrilow.

The Chairman of the Papers Committee.
The Chairman of the London Students' Section.

LIBRARY AND MUSEUM COMMITTEE.

The President.

Colonel R. E. Crompton, C.B.
Prof. E. W. Marchant, D.Sc.
Mr. S. W. Melsom.
Mr. W. M. Mordey.
Mr. C. C. Paterson, O.B.E.
Colonel T. F. Purves, O.B.E.

Local Centres Committee.

The President.

Mr. C. T. Allan.
Major H. Bell.
Mr. T. Carter.
Sir J. Devonshire, K.B.E.
Mr. K. Edgcumbe.
Mr. F. Gill, O.B.E.
Mr. J. S. Highfield.
Mr. E. M. Hollingsworth.
Mr. G. A. Juhlin.
Prof. E. W. Marchant, D.Sc.
Mr. R. B. Mitchell.
Mr. J. D. Morgan.
Mr. A. Page.
Mr. R. N. Tweedy.
Mr. C. H. Wordingham, C.B.E.

"Science Abstracts" Committee.

The President.

Mr. Ll. B. Atkinson.
Mr. W. R. Cooper.
Mr. F. Gill, O.B.E.
Mr. W. M. Mordey.
Dr. D. Owen, Mr. T. Smith — Representing the Physical Society of London.

Ship Electrical Equipment Committee.

The President.

Mr. A. G. S. Barnard.
Mr. J. H. Collie.
Mr. B. M. Drake.
Mr. A. Henderson.
Mr. J. W. Kempster.
Mr. J. F. Nielson.
Mr. N. W. Prangnell.
Major A. P. Pyne.
Mr. S. G. C. Russell.
Mr. T. A. Sedgwick.
Mr. H. D. Wright.
Mr. C. H. Wordingham, C.B.E.

And	*Representing*
Sir W. S. Abell, K.B.E.; Mr. J. T. Milton	Lloyd's Register of Shipping.
Two representatives	British Electrical and Allied Manufacturers' Association.
Mr. T. Carlton	Board of Trade.
Mr. W. Cross	Electrical Contractors' Association.
Mr. J. Foster King	British Corporation for the Survey and Registry of Shipping.
Mr. J. Lowson	Institution of Engineers and Shipbuilders in Scotland. Electrical Contractors' Association of Scotland.
Mr. A. W. Stewart	Institution of Naval Architects.
Mr. H. Walker, O.B.E.	N.E. Coast Institution of Engineers and Shipbuilders.

Wireless Section Committee.

Mr. E. H. Shaughnessy, O.B.E. (*Chairman*).

The President.

Mr. B. Binyon, O.B.E.
Mr. S. Brydon, D.Sc.
Dr. W. H. Eccles, F.R.S.
C. F. Elwell.
Prof. G. W. O. Howe, D.Sc.
Admiral Sir H. B. Jackson, G.C.B., F.R.S.
Mr. G. H. Nash, C.B.E.
Mr. C. C. Paterson, O.B.E.
Mr. J. St. Vincent Pletts.
Captain H. R. Sankey, C.B., C.B.E., R.E.
Dr. R. L. Smith-Rose.
Mr. A. A. C. Swinton, F.R.S.
Mr. C. F. Trippe.
The Chairman of the Papers Committee.

And	*Representing*
Capt. C. E. Kennedy-Purvis, R.N.	The Admiralty.
Major R. Chenevix-Trench, O.B.E., M.C.	The War Office.
Major H. P. T. Lefroy, D.S.O., M.C.	The Air Ministry.
Major A. G. Lee, M.C.	The Post Office.

Wiring Rules Committee.

The President.

Mr. Ll. B. Atkinson.
Mr. H. J. Cash.
Mr. J. R. Cowie.
Mr. W. Cross.
Mr. J. Frith.
Dr. C. C. Garrard.
Mr. P. V. Hunter, C.B.E.
Mr. S. W. Melsom.
Mr. J. F. Nielson.
Major A. P. Pyne.
Mr. E. Ridley.
Mr. C. P. Sparks, C.B.E.
Mr. C. H. Wordingham, C.B.E.

And	*Representing*
Mr. E. G. Batt; Mr. H. H. Berry; Mr. J. R. Dick; Mr. A. R. Everest; Mr. C. Rodgers	British Electrical and Allied Manufacturers' Association.
Mr. W. F. Bishop	Cable Makers' Association.
Sir T. O. Callender; Mr. J. F. W. Hooper	Cable Makers (unofficially).
Mr. W. R. Rawlings; Mr. S. H. Webb	Electrical Contractors' Association.
Mr. E. J. B. Lowdon	Electrical Contractors' Association of Scotland.
Mr. B. M. Drake	Contractors (unofficially).
Mr. A. C. Cockburn; Mr. S. G. C. Russell; Mr. A. L. Taylor	Fire Offices (unofficially).
Mr. J. Christie; Mr. F. W. Purse	Incorporated Municipal Electrical Association.
Mr. E. T. Ruthven Murray	Incorporated Association of Electric Power Companies.
Mr. O. M. Andrews	Conference of Chief Officials of the London Electric Supply Companies.
Mr. J. M. Crowdy	Association of Supervising Electricians.
Mr. T. Martin Harvey	Independent Cable Makers' Association.

Sectional Committees.

Lighting and Power.

The President.

Mr. J. W. Beauchamp.
Mr. J. R. Bedford.
Mr. R. A. Chattock.
Mr. R. Grierson.
Mr. A. F. Harmer.
Mr. R. B. Mitchell.
Mr. A. Page.
Mr. G. W. Partridge.
Mr. C. P. Sparks, C.B.E.
Mr. W. B. Woodhouse.

Electricity in Mines.

The President.

Mr. C. T. Allan.
Mr. J. A. B. Horsley.
Mr. J. D. Morgan.
Mr. W. C. Mountain.
Mr. W. H. Patchell.
Mr. W. M. Selvey.
Mr. C. P. Sparks, C.B.E.
Prof. W. M. Thornton, D.Sc., O.B.E.
Mr. W. B. Woodhouse.

SECTIONAL COMMITTEES—*continued.*

Traction.

The President.

Mr. H. W. Firth.
Lt.-Col. F. A. Cortez Leigh.
Mr. F. Lydall.
Mr. A. H. W. Marshall.
Mr. G. W. Partridge.
Mr. J. Sayers.
Mr. R. T. Smith.
Mr. B. Welbourn.
and one other to be appointed.

Electro-Chemistry and Electro-Metallurgy.

The President.

Mr. W. A. Chamen.
Mr. W. R. Cooper.
Prof. W. Cramp, D.Sc.
Mr. S. E. Fedden.
Mr. E. M. Hollingsworth.
Mr. W. M. Morrison.
Mr. J. Swinburne, F.R.S.,
and 2 members to be co-opted by the Committee.

Telegraphs and Telephones.

The President.

Mr. H. G. Brown.
Mr. W. W. Cook.
Dr. W. H. Eccles, F.R.S.
Mr. S. Evershed.
Mr. H. H. Harrison.
Mr. G. H. Nash, C.B.E.
Col. T. F. Purves, O.B.E.
Mr. J. Sayers.
Mr. C. W. Schaefer.
Mr. F. Tremain.

Representatives of the Institution on Other Bodies.

The following is a list of representatives of the Institution on other bodies, and the dates on which they were appointed.

Birmingham Chamber of Commerce:

Mr. S. T. Allen (27 March, 1919).

Bradford Public Libraries Committee:

Mr. T. Roles (27 Feb., 1919).

Bristol University:

Mr. H. F. Proctor (6 Dec., 1917).

British Association, Fuel Economy Committee:

Mr. C. H. Wordingham, C.B.E. (9 Jan., 1919).

British Electrical and Allied Industries Research Association:

Mr. Ll. B. Atkinson (2 April, 1919).
Mr. F. Gill, O.B.E. (2 Nov., 1922).
Mr. R. T. Smith (30 Oct., 1919).
Mr. C. P. Sparks, C.B.E. (4 Oct., 1917).
Mr. C. H. Wordingham, C.B.E. (4 Oct., 1917).

Sectional Committee on Electric Control Apparatus Research:

Major H. C. Gunton (2 Feb., 1921).
Mr. C. H. Wordingham, C.B.E. (22 Nov., 1920).

British Electrical Development Association:

Mr. R. Hardie (18 Jan., 1923).
Mr. C. H. Wordingham, C.B.E. (18 Jan., 1923).
(One vacancy.)

British Empire Exhibition, 1924, Electrical and Allied Engineering Committee:

Sir A. M. Ogilvie, K.B.E., C.B. (23 June, 1922).

British Engineering Standards Association:

Main Committee:

Col. R. E. Crompton, C.B. (18 Jan., 1923).
Mr. Ll. B. Atkinson (1 Feb., 1923).
Mr. C. H. Wordingham, C.B.E. (18 Jan., 1923).

Sectional Electrical Committee:

Mr. F. Gill, O.B.E. (21 May, 1914).
Mr. J. S. Highfield (21 May, 1914).
Mr. R. T. Smith (21 May, 1914).
Mr. W. B. Woodhouse (19 Dec., 1918).
Mr. C. H. Wordingham, C.B.E. (18 Nov., 1915).

Sectional Committee on British Standards in Colonial and Foreign Trade:

Mr. C. P. Sparks, C.B.E. (26 Oct., 1916).

Sectional Committee on Machine Parts and their Gauging and Nomenclature:

Mr. J. H. Rider (8 Feb., 1917).

Sectional Committee on Petroleum Products:

Mr. H. W. Clothier (1 Feb., 1923).

Electrical Instruments Sub-Committee:

Mr. K. Edgcumbe (15 Feb., 1923).

Electrical Nomenclature and Symbols Sub-Committee:

Mr. C. C. Paterson, O.B.E. (8 Jan., 1920).

Overhead Transmission Lines Material Sub-Committee:

Mr. C. H. Wordingham, C.B.E. (30 Oct., 1919).

Pipe Flanges Sub-Committee:

Mr. W. M. Selvey (14 April, 1921).

Panel on Steel Conduits for Electric Wiring:

Mr. H. J. Cash (28 Sept., 1922).
Mr. J. M. Crowdy (28 Sept., 1922).

Conference on Standardization of Ball and Roller Bearings:

Mr. W. M. Selvey (26 July, 1921).

Darlington Board of Invention and Research:

Mr. R. M. Longman (15 May, 1919).
Mr. J. R. P. Lunn (15 May, 1919).
Mr. H. G. A. Stedman (15 May, 1919).

Engineering Joint Council:

Mr. J. S. Highfield (15 Feb., 1923).
Mr. R. T. Smith (15 Feb., 1923).

Imperial College of Science and Technology, Governing Body:

Mr. W. M. Mordey (12 April, 1923).

Imperial Mineral Resources Bureau Conference:

Mr. J. H. Rider (23 Jan., 1919).
Mr. W. B. Woodhouse (23 Jan., 1919).

Copper Committee:

Mr. B. Welbourn (18 Sept., 1919).

Miscellaneous Minerals Committee:

Prof. E. Wilson (18 March, 1920).

Institute of Metals, Corrosion Research Committee:

Mr. W. M. Selvey (19 July, 1923).

Institution of Civil Engineers, Engine and Boiler Testing Committee:

Mr. R. A. Chattock (19 Oct., 1922).
Mr. C. P. Sparks, C.B.E. (19 Oct., 1922).

Institution of Heating and Ventilating Engineers, Committee on Utilization of Exhaust Steam and Waste Heat:

Mr. P. V. Hunter, C.B.E. (29 Sept., 1922).
Mr. W. M. Selvey (29 Sept., 1922).
Mr. J. C. Wigham (29 Sept., 1922).

International Illumination Commission, British National Illumination Committee:

Prof. W. C. Clinton (13 Dec., 1917).
Mr. K. Edgcumbe (27 Nov., 1913).
Mr. Percy Good (18 Sept., 1919).
Mr. H. T. Harrison (27 Nov., 1913).
Prof. J. T. MacGregor-Morris (27 Nov., 1913).

International Navigation Congress, 1923, General Organization Committee:

Mr. F. Gill, O.B.E. (2 Feb., 1922).

International Road Congress (Fourth):

Col. R. E. Crompton, C.B. (6 July, 1922).

International Scientific Unions:

Committee on International Union in Physics:

Dr. A. Russell (18 March, 1920).

Committee on International Union in Radio-Telegraphy:

Dr. W. H. Eccles, F.R.S. (18 March, 1920).
Prof. G. W. O. Howe, D.Sc. (18 March, 1920).
Prof. E. W. Marchant, D.Sc. (18 March, 1920).

International Testing Association:

Mr. Ll. B. Atkinson (29 May, 1919).
Mr. C. C. Paterson, O.B.E. (29 May, 1919).

Leeds Civic Society:

Mr. E. C. Wallis (27 March, 1919).

Leeds Municipal Technical Library Committee:

Mr. W. B. Woodhouse (19 Dec., 1918).

Loughborough Technical College, Advisory Committee:

Mr. R. B. Leach (27 March, 1919).

Metalliferous Mining (Cornwall) School Governing Body:

Mr. J. S. Highfield (18 Sept., 1919).

Middlesbrough Technical College, Governing Body:

Mr. C. O. Brettelle (1 Oct., 1923).
Mr. P. S. Thompson (1 Oct., 1923).

Mines Department, Electrical Storage Battery Locomotive Committee:

Mr. R. T. Smith (7 Dec., 1922).

National Physical Laboratory, General Board:

Mr. Ll. B. Atkinson (21 Oct., 1920).
Dr. A. Russell (22 Nov., 1923).

Newcastle-upon-Tyne Chamber of Commerce:

Major A. P. Pyne (13 Nov., 1919).

Paris Conference on E.H.T. Lines, 1923:

Mr. P. V. Hunter, C.B.E. (1 Feb., 1923).
Mr. E. B. Wedmore (1 Feb., 1923).
Mr. W. B. Woodhouse (1 Feb., 1923).

Paris Conference on Weights and Measures:

Sir R. T. Glazebrook, K.C.B., D.Sc., F.R.S. (14 April, 1921).
Dr. A. Russell (14 April, 1921).

Professional Classes Aid Council:

Mr. W. B. Esson (26 July, 1921).

Registration of Electrical Contractors:

Mr. P. V. Hunter, C.B.E. (12 April, 1923).
Mr. W. R. Rawlings (15 March, 1923).
Mr. W. M. Selvey (15 March, 1923).
Mr. C. H. Wordingham, C.B.E. (15 March, 1923).

Röntgen Society Advisory Committee for British X-ray Industry:

Dr. W. H. Eccles, F.R.S. (21 Feb., 1918).
Mr. J. E. Taylor (21 Feb., 1918).

Royal Engineer Board:

Mr. C. H. Wordingham, C.B.E. (7 April, 1921).

Royal Society:

Alloys of Iron Research Committee:

Mr. J. Swinburne, F.R.S. (15 Feb., 1923).

National Committee for Physics:

Dr. A. Russell (16 Dec., 1920).

National Committee on Radio-Telegraphy:

Dr. W. H. Eccles, F.R.S. (4 Aug., 1920).
Prof. E. W. Marchant, D.Sc. (4 Aug., 1920).

Scientific and Industrial Research Advisory Council, Engineering Committee:

Mr. J. S. Highfield (9 March, 1916).

Society of Radiographers:

Dr. W. H. Eccles, F.R.S. (22 Jan., 1920).
Mr. J. S. Highfield (22 Jan., 1920).
Mr. C. C. Paterson, O.B.E. (22 Jan., 1920).
Dr. A. Russell (25 May, 1922).
Mr. A. A. C. Swinton, F.R.S. (22 Jan., 1920).
Mr. C. H. Wordingham, C.B.E. (22 Jan., 1920).

Transport Ministry, Advisory Panel and Committees:

Mr. Ll. B. Atkinson (30 Oct., 1919).
Sir J. Devonshire, K.B.E. (30 Oct., 1919).
Mr. J. S. Highfield (30 Oct., 1919).
Mr. R. T. Smith (30 Oct., 1919).
Sir John Snell (30 Oct., 1919).
Mr. C. P. Sparks, C.B.E. (30 Oct., 1919).
Mr. C. H. Wordingham, C.B.E. (30 Oct., 1919).

Women's Engineering Society:

Mr. A. P. M. Fleming, C.B.E. (19 July, 1923).

World Power Conference, 1924:

Mr. Ll. B. Atkinson (12 April, 1923)
Mr. R. T. Smith (12 April, 1923).
Sir John Snell (12 April, 1923).

INDUSTRIAL RESEARCH, WITH SPECIAL REFERENCE TO ELECTRICAL ENGINEERING DEVELOPMENT.

By W. WILSON, B.E., M.Sc., Member.

(*Paper first received* 31*st October*, 1922, *and in final form* 6*th December*, 1923; *read before* THE INSTITUTION 1*st November, before the* NORTH-EASTERN CENTRE 12*th November, before the* SOUTH MIDLAND CENTRE 14*th November, before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 19*th November, before the* NORTH MIDLAND CENTRE 27*th November, and before the* DUNDEE SUB-CENTRE 13*th December*, 1923.)

SUMMARY.

During the past 40 years radical changes in manufacturing conditions have rendered industrial research essential for the attainment of reasonable efficiency and progress.

Industrial research is divisible into two orders, the more general and the more particular, both being necessary for the production of a new article. The second is usually termed "Development," and is the special subject of this paper.

While British men of science and applied science have been pre-eminent for general research, little attention has been paid to development. Hence few inventions have, within recent years, been brought to their conclusion in this country, as compared with the great amount of original scientific work which has been successfully accomplished.

The reasons for this are analysed, and the cause is traced to lack of the co-operation necessitated by modern manufacture. This want is filled by development departments.

The various functions of the latter are dealt with. Their outcome is the removal of all non-standard work and technical troubles from the shops and drawing offices, and the provision of original and matured designs of new and improved articles for manufacture.

The negligible value of ordinary sources of novel suggestions is discussed, and the qualifications of a development man are deduced. The question of staffing the department, and the educational qualifications which the staff should possess, are then treated.

Practical matters, including buildings and equipment, procedure in development, the recording and filing of results and data, and the indexing of literature and information, are discussed.

A short summary is given of the principal industrial research organizations in Great Britain, with a brief discussion on co-ordination.

TABLE OF CONTENTS.

I. INTRODUCTION.

The past 40 years have witnessed a gradual but far-reaching change in the manufacturing system. In the first place, the increasing application of science to industry, and the growing complexity of the various products, have in general made it impossible for a single mind to carry on the complete administrative and technical direction of a manufacturing business. Secondly, the progressive standardization of all but the newest products has opened the way for quantity production, involving the manufacture of a greatly increased number of articles on the basis of a given design, and has thus introduced conditions favouring the growth of the factory and at the same time the specialization of its output.

Not only have these developments enhanced the value of the original design, since a much greater number of articles are now affected thereby, but the increased efficiency introduced by quantity production has afforded the means whereby the design can be far more fully considered. Thus the scientific staff has found a place in manufacture. Their work has been generally termed "industrial" research, in contradistinction to the "pure" research carried on for the extension of scientific knowledge.

The former is divisible into two well-defined orders; the first being the more general and theoretical, and the second the more particular and practical. Of these, the second is generally termed "development" and has been brought to a high state of perfection abroad. In this country its value has been recognized to a much smaller extent, to the disadvantage of many of our industries. The author is convinced that no procedure is more capable of benefiting the industry with which we are more especially concerned than the institution and furtherance of developmental research; and it is the purpose of this paper, first to distinguish between the various kinds of research and their application, and then to deal particularly with the essentially practical variety.

II. CLASSES OF RESEARCH WORK.

The above three types of research work are typically employed in consecutive order, in the production of new pieces of apparatus. First, an investigator in a university or similar laboratory makes a discovery while engaged in extending scientific knowledge. Secondly, a worker in an industrial research institution recognizes the possibility of utilizing the discovery in connection with his industry, and carries out a further investigation to ascertain its practicability. If the answer is in the

affirmative he makes a definite proposal, and may even support this with a primitive model. Finally, a development worker takes the matter in hand and, as a result of a third investigation, elaborates an actual product embodying the principles evolved by his two predecessors. The proposed apparatus, as submitted to him, may be fragile, inefficient, unreliable and expensive, its utilization being unwarranted or even impossible until various practical problems have been solved. This, then, is the function of the third class of worker, who renders the apparatus suitable for manufacture in the shops and for acceptance in the commercial field.

These three stages can be clearly recognized in the evolution of practically every industrial apparatus. Of these it will be sufficient to cite the dynamo as an instance. First, the production of force by electromagnetic means was investigated, notably by Oersted, Ampère, and Barlow, the last-named of whom actually obtained continuous rotary motion. On these principles Faraday then based his more utilitarian but extremely important investigations, leading to the construction of the first crude dynamo. Finally, the latter was developed to its practical form by Gramme, Crompton, Kapp, Ferranti, Hopkinson and others.

The distinguishing characteristics of the three orders may now be summed up. Pure research, to employ its usual but not highly satisfactory name, is unique in being undertaken entirely with a philosophic motive, and hence would probably be best described as "philosophic" research. In this respect it is contrasted with "industrial," "utilitarian," or "pragmatic" research, by which a proposal for an article of commercial utility is formulated. This proposal is converted into a finished and workable apparatus by what is most often known as "development," a title that is, however, ambiguous when its context is not supplied; and as practically the same ground is covered by the "technical research" of Mr. Swinburne, the latter term is preferred by the author.

III. Need for Technical Development.

If the evolution of modern engineering products is studied, it will be found in a surprisingly large number of cases to have been the outcome of pioneering work done in this country, which has unfortunately been discontinued at the end of the second stage, leaving the final development to be carried out abroad. A few examples of this may be worth recalling.

The industries depending upon the fixation of atmospheric nitrogen are the outcome of the philosophic research work of Priestley and Cavendish, followed by the more utilitarian investigations of Rayleigh. The development work was carried out abroad, largely in America and Norway. Other electrochemical products, derived largely from the researches of Davy, Faraday and Charles Watt, have only resulted in the establishment of new industries in Germany. Several types of alternating-current motor have the same history. Electrical engineering generally has been founded chiefly on the brilliant work of great British electricians, such as Faraday, Maxwell, Kelvin, Hopkinson and Thompson, yet much of the work of application and development has been carried out in America and on the Continent, while quite a considerable proportion of the apparatus actually manufactured in this country during recent years has been made to designs supplied from abroad.

Unfortunately, although we claim for our own technical men very much of the credit for industrial progress, it is those who complete the work that gain every other advantage, for we have grown accustomed to abandoning our enterprises just where they begin to be profitable. By permitting foreign nations to act before us in this manner we are conceding them the initiative, an error in tactics as serious in commerce as in war. In the Colonial and foreign fields the effect of this loss of initiative is especially evident, for prestige is there an important factor in determining success, and orders tend to be given to the actual authors of improvements and innovations. The latter also secure the very practical advantage that they turn out the improved product, and therefore give better value, for a considerable period before their copyists.

IV. Causes of the Present Position.

From time to time, theories of rather an alarmist nature are propounded to explain this state of things, usually by the allegation of national decadence in various respects. Such charges of deterioration cannot, however, be substantiated either against our investigators in pure or applied science or against the workers in our factories. Further, the outstanding success of our invention and manufacture during the war, not only in a few but in practically all industries, sufficiently proves our originating capacity. It is evident, therefore, that there must be a national peculiarity the effect of which was unfelt, or at least unnoticed, until manufacturing conditions were disturbed by the developments in industrial methods to which reference has been made.

Such a characteristic is to be found in the tendency against co-operation that is at once remarked even by a newcomer to this country from another part of the British Dominions. It is evident in our art, in our politics, and in our industries. Its effects are apparent not only between individuals, but between associations, between firms, between those who teach the theory and those who practise the profession. Its result is that for single-handed work we need fear no competition, but where co-operation is essential we frequently fail.

Unfortunately for us, the present industrial era is one in which the association of effort and of ideas is all-important. In every movement a time arrives when progress can be maintained only by co-ordination. This critical point was reached in engineering development when the foundations had all been laid, when the elementary discoveries had all been effected, and when the simple apparatus had all, or nearly all, been thought out. From then onwards, progress could only be made on more advanced lines, by employing higher theoretical principles, more elaborate tools and instruments, and more expensive construction. For this, not only is scientific work necessary, but most of it must be carried out in conjunction with the industry, and much of it in conjunction with the actual works. These two latter categories will be recognized as broadly corresponding to industrial research and development respectively.

The latter is unfortunately attended by peculiar difficulties, since it must be carried on by men of university status, in conjunction with a factory or group of factories, and these two elements have in this country proved very hard to combine. The author hopes that a discussion of the problems involved will be of advantage in furthering this form of research work, and thus in promoting the welfare of the industry.

V. Functions of a Development Department.

The broad function of a development department is to evolve new types of product for manufacture in the shops with which the department is associated. This also involves the evolution of new parts for an existing model, to endow the latter with new characteristics or to improve it in some desirable respect. In many cases the designing and drawing offices may themselves be able to effect a desired change, and merely require certain theoretical or experimental information which, on request, is then supplied by the development staff. Problems requiring higher mathematics will be submitted to them for solution. Problems and difficulties in the examination of the finished product will be passed on by the routine testing or inspection departments. Technical advice will also be afforded to any part of the factory when desired.

The general effect of such a department is to take upon itself all technical burdens from the shoulders of the staff and works. It thus incidentally performs two very important services. First, much of the worry and risk of failure is removed from the designing staff, and secondly, all work of a non-standard nature can be removed from the shops, as the model makers attached to the development department will now carry out all experimental or tentative construction. Those who are intimately concerned with manufacturing will have had experience of the absorption of time and disarrangement of routine that may be caused by the sandwiching of trial jobs between the regular items of work, and by the frequent visits of draughtsmen to the work benches. The aim of the development system is to put an end to this, and to enable both shops and staff to pursue their duties with a minimum of interruption.

In order to illustrate the above curriculum and to demonstrate its general applicability, the author proposes to outline the actual work to be carried out in two specific cases, so selected as to represent opposite extremes.

The first case is that of a factory employing several thousand hands, all engaged on mass production. It will be supposed that the designs are supplied to the factory in question by their customers, as was the case with munition firms during the war.

The peculiarity of such a works is that there is no apparent necessity for any theoretical department, if a materials test-room be excepted, and it is by no means unknown for a factory of this nature to be organized with no special provision for technical knowledge. The manager and foremen may be what are euphemistically called "practical men," i.e. they may be promoted workmen who have never received any technical training. Even the head of the gauge room may be a fitter with no knowledge of science or mathematics and no aptitude for study. It is possible, in short, for a factory with a pay-roll running into four or five figures, to include no more than about a dozen people, apart from the clerical staff, whose education has continued after they were 14 years of age.

Yet there are frequent problems, even in repetition work, that require solution by a highly trained man. The type of machine used in a modern workshop, the jigs, fixtures, and other machining accessories, and especially the gauges, have been designed with the assistance of all the resources of modern engineering science, and their use should therefore require a corresponding degree of knowledge in the workshop. In particular, limit-gauging is a definite and intricate branch of physical science, and proficiency in it demands a knowledge of geometry, trigonometry, applied mechanics and the properties of materials.

Keeping the factory as a whole just as it is, an immediate gain in efficiency out of all proportion to the cost would be effected by the institution of a small development department, the chief duties of which would be to act as consultant to the shops. Even one man with, say, a university degree in engineering and an enthusiasm for the work, would be able to reduce greatly the amount of scrap and to cause things to go more smoothly. He would be consulted if a gauge gave unsatisfactory results, and would be required to discover the reason and to correct the method of gauging employed. Jigs that were misdirecting their drills for some obscure reason would be put under his observation. Theoretical questions as to materials, illumination, heat treatment, rectification, and the like, would be put to him. He would suggest, or search for, scientific methods of overcoming the many small difficulties that crop up in such a works, while he would keep in touch with the general workshop practice applicable to his particular establishment.

As these functions do not, in point of fact, involve investigations of a very advanced nature, but do involve a close contact with the shops, the department might well include a small technical library for the use of the works staff, by the administration of which the head could the more effectively get, and keep, in touch with those in charge of the work, who would thus be the more ready to bring problems and troubles to him for solution.

The second and more advanced example is a department associated with an electrical factory, which is entirely self-contained, in that the whole of its products are designed within its walls. To begin with, the development staff will endeavour to produce new designs of apparatus for the shop to manufacture. Much of this work will be undertaken as a result of representations from the various sales, design, works or other departments, whenever one of these may realize that a change or an innovation is desirable. The development staff will also keep in close touch, by study and observation, with electrical practice as it concerns their products, and will thus themselves be able to initiate proposals as to future activities. These will be submitted to the management through the medium of reports, in which the objects of the proposed developments are given,

together with such details as to their nature as have been arrived at.

Since the development department in such a factory is either the point of origin or the clearing house for new products, it follows that it must be the repository for all technical data concerned in the design of the articles made in the factory. No development with which the department is not made acquainted, however trivial it may be, should be permitted in the shops. It would be absurd to assume that no member of the regular office or works staff is capable of introducing original improvements or novelties, and it is perhaps scarcely necessary for every single item of experimental design to be made up in the development shop or even under the surveillance of one of the development staff. But it may be stated definitely and emphatically that if the department is to be efficient in its functions it must know the whole truth with regard to the design and performance of all the products for which it is responsible. Draughtsmen and foremen are exposed to a natural temptation to experiment for themselves with models in the shops and test-rooms. This procedure re-introduces non-standard work into the factory curriculum; at the best it constitutes double-banking; it is a most expensive practice when everything is taken into account; and an efficient and economical outlet for such energy is now provided. Such people should be instructed to communicate their proposals in full to the development department, and any attempt at "private enterprise" should be strictly repressed.

The duty of being responsible for all data connected with design and performance thus devolves on the department. Careful records of constants, standards, specifications and dimensions employed in current design; modifications; test results; complaints received; patents taken out and pending; and suggestions, are compiled and indexed. An index of information bearing on subjects connected or allied with those under investigation must be created, preferably on the card system.

These records can only be rendered complete and therefore dependable if every unusual occurrence that bears in any way upon design is reported to the department. They also render the development staff fully capable of acting in a consultative capacity to the factory in general, and of dealing with a wide variety of technical queries. Calculations involving higher mathematics, such as the force between adjacent conductors due to a possible short-circuit, or the strength of spring required to generate a required velocity in the contacts of an oil switch, will be submitted to them. Simple formulæ or diagrams, whereby such values may be obtained by the factory staff, will, where possible, be worked out. Questions involving theory, such as the resultant current in portions of a network, the safe current density in a liquid, or the treatment of an accumulator battery, will also be addressed to the department. Test-apparatus for given requirements will be specified, designed or even constructed for the routine test-rooms. Inquiries, even of the "workshop recipe" type, may be made and answered by means of an appropriate file or index.

When a complaint is received from a customer the development department will act as an adjudicator for the firm, examining the apparatus in question and the conditions under which it failed, bestowing the blame in the right quarter and proposing a remedy.

The examination of materials comes, in reality, within the scope of routine testing; but as such work is of small extent, and requires expensive and delicate apparatus that is also necessary for development work, an exception may be made in this respect, and such routine work may be done in this department. The same arguments apply to the calibration of instruments; and those for the whole factory may, without introducing inefficiency into the development system, be adjusted and even repaired in the department's laboratory. Apart from these exceptions, routine work is out of place in a development laboratory, and its introduction is most undesirable.

From the above functions it will be seen that a very considerable burden is removed from the works and drawing office, and the result must be smoother and easier working, economy of labour and certainty of result.

VI. The Value of Suggestions.

It has already been stated that the development department is the correct place for receiving, examining and reporting on suggestions from outside its own walls, and efficient arrangements should be made for doing so. The benefit derived from this source is, however, much less than is generally imagined.

There is a popular theory that an epoch-making discovery in any branch of science may be made by anyone with a smattering of knowledge therein. A similar delusion is that workpeople and humble employees of big firms contribute largely towards the "new ideas" which help the firm to make a profit. If it were more fully realized that such discoveries can be made only by people who are earnestly searching for them, and who also know from long experience how and where to look, not only would considerable misconception be prevented but much disappointment to would-be inventors, and much loss to the investing public, would also be saved.

Some years ago the author was engaged as a consultant to report on a new reversible steam turbine, a 20-h.p. model of which had been constructed and operated under steam for demonstration purposes. The inventor was a mechanic with no training or experience to equip him as a turbine designer, but nevertheless a company was formed and registered and the shares were upon the market prior to any competent advice being obtained by the directors. A cursory examination then revealed that it was not a turbine at all, but a crude, rotary piston engine, and a brief test showed its efficiency to be in the vicinity of 1 per cent. It is interesting to note that this information led to the abandonment by the directors, not of the project, but of the consulting engineers, leaving the company to go forward and the shareholders' money to be lost without expert counsel.

The above instance, which is only typical of many such failures, has been given to illustrate the extent of the popular misconception, even among business men, as to the simplicity of arriving at valuable results. Contrary

to this mistaken view, it is practically impossible for an investigator to produce a novel apparatus unless he possesses a number of valuable qualifications. First, he must be well versed theoretically; secondly, he must be intimately acquainted with the practical conditions, and especially the worst conditions, under which the apparatus is to function; thirdly, he must be informed as to the work which has already been done on the same type of apparatus, including the failures of other workers; and finally, he must have practical knowledge of the methods of manufacture appropriate to the apparatus. The weaker he is with respect to any of these qualifications, the more the success of his efforts depends upon chance, and the more wasted work he does in a given time. These points may be strengthened by a further and more simple illustration.

One of the most attractive articles to amateur designers in the realm of switchgear is the fuse, and probably more worthless suggestions are made in connection with this appliance than any other. Its action and principle appear to be easy to understand, while the shortcomings of the standard patterns seem evident and regrettable. It is therefore inevitable that a number of would-be improvements should be designed, the defects of which illustrate the need of the qualifications that have been mentioned.

In the first place, the vast majority of their producers do not realize that a fuse has to do something more than open the circuit upon the occurrence of a small overload, up to, say, twice the normal load. If this were all, almost any enclosure containing the wire would serve the purpose. The governing condition, however, is that of a short-circuit, and the problem thus becomes much more abstruse. As a matter of fact, the standard test for a fuse is to connect it across the mains with the containing case "earthed" to the positive, and then to close the switch.

Besides familiarity with the requirements, fuse design demands a knowledge of the properties of the electric arc, as its success depends upon its power of quenching an arc stream before any appreciable damage has been done to the contacts or porcelain. A knowledge of the materials that may be involved, together with the method of working them, is also desirable, in order that sound and economical construction may be specified. Finally, all the work expended on design will be wasted if the resultant fuse is one which has been tried and discarded a number of years previously.

The fact that emerges from these examples is that the person whose suggestions are likely to prove of value is the one who is actively engaged in producing or otherwise dealing with the article in question. For example, the staff of the department itself, including assistants, model makers and juniors, become potential discoverers in their own spheres, especially if an atmosphere of research can be made to permeate the whole establishment and collective thinking is encouraged.

It is also natural that valuable proposals should emanate from the designing and drawing offices, the staff of which includes men with the necessary qualifications for at any rate the less advanced forms of invention. Here again, useful results may be few unless a certain favourable atmosphere can be created and maintained.

Such proposals from the shops as are acceptable are usually for improvements in methods of working, and for safeguarding the operators themselves from injury. The author is in favour of stimulating the workpeople by the standing offer of a monetary reward when such suggestions are used.

Outside the factory, suggestions are offered chiefly by customers and patentees. The former, as users or potential users of the firm's products, are in a radically different position from the producers with regard to the apparatus, and any comment from them affords data for design. A patentee's proposal is usually accompanied by a specification, which requires to be digested and reported upon to the management, who then take up the negotiations.

Even when a suggestion is sound it is not always possible to employ it at once, as the modification of the standard design will not always be justified for the sake of a single improvement. Such suggestions are therefore carefully filed for use in the immediate future.

VII. Staff.

The preceding section will have indicated how many people are *not* in a position to contribute original ideas, and will have emphasized the value of a development staff who are able to collaborate upon their special functions, unimpeded by commercial matters or the regular routine work of the factory.

A first great advantage derived from the segregation of the men engaged upon development is that their qualifications are largely pooled, and individual members can do original work although each does not possess all the stated qualifications. For example, an enterprising and well-educated but inexperienced junior might still bring forward valuable suggestions when helped and guided by his older and more experienced colleagues. It is necessary, however, that the senior men, and especially the head of the department, should be "all-round" men. The head himself should have as wide and general an experience as possible in the use of the articles to be developed, as it is upon him that the responsibility rests for the practical utility of the department's products. Again, the senior men, and especially the head, should have had considerable shop experience in the construction of such products.

It must not be imagined that anyone who fulfils the conditions given in Section VI above will succeed in a development department. These were intended to be the bare essentials for the making of useful suggestions, and must be reinforced by others if difficult problems are to be solved and elaborate designs arrived at.

In the first place a research man must have an analytical mind, or in other words a faculty of isolating the various components of a problem, of separating the vital from the secondary, and of distinguishing and correlating cause and effect. He must be an adept at eliminating interfering elements from his considerations, arguments and tests. In particular, he must be able to refer as many problems as possible to first principles, in order that the simplest, clearest and surest thinking may result. By virtue of this faculty, an involved and therefore a great difficulty may be broken up into a number of separate problems, the solution of which can

then be carried out in turn. Without it, the would-be research worker cannot hope to penetrate far beneath the surface without becoming confused.

Although it is probably going too far to assert that the above qualifications can be conferred by any course of study upon an individual who is not specially gifted by nature, it is a fact that they can be awakened and enormously stimulated by appropriate training. In the case of one who hopes to attain a leading position in technical research and to exercise the functions that have been described, the following preparation is indicated :—

A. General training.

(1) Training in the art of clear and logical thinking, afforded by the study of mathematics.

(2) Training in the tactics of research, afforded by a study of physics and chemistry and, if possible, of geology.

(3) Training in the art of lucid expression, afforded by the study of languages.

(4) Training for the hand and eye, afforded by the study and practice of mechanical drawing.

(5) Training in the practical application of theory, afforded by works experience as nearly concurrent with the theoretical training as possible.

*B. Special training.**

(1) Advanced study of the principal pure science concerned in the industry (electricity and magnetism).

(2) Study of the applied sciences bearing on the subject (at least applied mechanics, mechanics of machinery, theory of structures, strength of materials, and heat engines).

(3) Study of the professional subject concerned (electrical engineering).

(4) Study and practice in design (electrical design).

It will be seen that a full professional degree course has been arrived at, the pure science subjects of which the author considers to be especially valuable for the purpose in hand. Not only does a study of the work done by the great scientific investigators of the past help the student to acquire some of their ingenuity, their perseverance, their thoroughness and their courage, but the attendant laboratory practice affords the much needed ability of drawing correct inferences from experimental work.

The necessary works experience after graduation should be obtained preferably as a regular employee, and not as a privileged "hanger-on." In addition, the inspection of works concerned with collateral industries is especially valuable as an antidote to a "water-tight compartment" tendency that frequently cramps development.

A few words may be said with regard to the type of men required for various kinds of research work. For some branches, such as magnetic survey work, stolid, even-natured men are needed who can work for 14 hours a day at monotonous occupations, without complaint or desire for relaxation. But most members of a technical research staff must rather be capable of concentrating a great amount of energy upon a problem and need not have the same virtue of constancy of effort. For invention and the solution of difficulties, moreover, the qualities of imagination and enthusiasm are at a premium, and these are characteristics of the excitable, rather than the stolid, type of man. A third type, intermediate between the foregoing, includes mathematical investigators.

A characteristic of a research staff, as distinct from the components of a works organization, is that they are not only engaged entirely on brain work, but the tasks of many of them, notably of those belonging to the second type, are practically all inherently high-pressure ones, almost unmixed with work of a regular description. To avoid as far as possible the risk of mental or nervous overstrain, a few special points are worthy of note. First, a development department exists to relieve the rest of the factory of worry, and every care should therefore be taken that ordinary worries, such as "chasing" materials and plant, are spared them. Secondly, "rush jobs" should be given to them as sparingly as possible, for, although an investigator can generally rise to an occasion, the process of obtaining inspirations to order may be a very exhausting one, especially if he is already fatigued or is concentrating at the time on some other problem. Thirdly, his data should be accurate, and should, if possible, be first-hand, for these are apt to get sadly emaciated if they come to him verbally through an intermediary. Finally, due appreciation should be accorded to the work when it is done. One of the greatest incentives to an investigator is the feeling that he is about to effect a permanent improvement in the performance, manufacture or cost of some product. If, after he has solved some problem that has been set him, he sees the results of his efforts pigeon-holed or otherwise neglected, this incentive is apt to weaken considerably.

With regard to juniors, there are two types who do not require the educational qualifications that have been specified. The first of these belongs to a class of man who is not ambitious of rising to the top, and is content to go on performing the same duties almost indefinitely. It cannot be denied that such men are useful, as they can be put in charge of some specific branch of testing or other work and can be relied upon to continue doing this without further trouble after their original instruction. The author's preference, however, is to feel that every subordinate is endeavouring to improve himself, even if it means occasional temporary inconvenience through staff changes. This policy would appear to accord better with the nature of the whole department. The other type is the improver, who spends a period in the laboratory to complete his experience prior to going out to represent his firm in the capacity of branch engineer or salesman. He will already have had a secondary education, and should have followed this up by at least an evening course at a technical school. These men also have their uses as assistants in the test rooms, or in other respects, if they are conscientious ; but if they regard themselves as passengers who do not need to "make good," they are worse than useless and should be rejected when these signs develop.

The model-makers should be careful mechanics of the tool-room variety, selected for accuracy and keenness

* The subjects given in brackets are those appropriate for electrical engineering development.

rather than for rapidity. Rather more than the usual intelligence is necessary, as they will be required to work from continually changing drawings, many of which will not be fully detailed.

VIII. Buildings and Equipment.

There is no need to devote much space to the question of buildings, as this part of the subject has been very fully treated in a paper by Mr. A. P. M. Fleming.* The building with which the author is most familiar is, as a matter of fact, somewhat on the lines of Fig. 9 in that paper, but with a somewhat greater floor area. In order, however, to include the cases of small firms who may not be in a position to erect separate premises at the outset, but who nevertheless have much to gain from technical research, a few additional remarks are given especially to cover their requirements.

The most serious mistake that can be made when a research department is being instituted, and when its site and equipment are under consideration, is to adopt as a guiding principle that the proposed new section will not produce output, and that it must therefore take second place to any part of the factory that does. It is most advisable that the tendency to make this assumption be carefully borne in mind, especially when the site and equipment are being decided, and when there is a possibility of the new department being seriously handicapped from the start by unsuitable selection in these respects.

It must be made clear from the outset that the development staff are going to exercise a great beneficial effect upon production, and that anything which impedes their work is going to impede output. Furthermore, they are about to improve the quality of the work done in the factory, and anything that interferes with the excellence of their work will similarly effect the products of the shops. An inferior lathe in the main machine shop will handicap the work of one operator; but one such machine in the development shop will risk the spoiling of the design of every article made on the basis of every model for which the lathe is used.

The principal requirement as to site is absence of noise, especially spasmodic noise such as is caused by the tipping of castings. If this were to happen within close earshot of a man engaged in concentrated thought upon some intricate problem, the consequence would be not only to break the thread of his thoughts completely, but to administer a shock to his nervous system which, upon reiteration, would produce serious consequences.

A further point bearing upon the question of comfort, when use is to be made of an existing room, is the necessity for adequate heating. It frequently occurs that one of the staff will spend long periods in complete bodily inaction, and his office then needs the highest standard amount of heating. In the event of a store or workroom being converted, this should be taken into account, as a lower degree of heating is appropriate for both of these.

The author desires to endorse the stress laid by Mr. Fleming upon the avoidance of vibration for the testing and experimental section. Many pieces of apparatus such as reverse cut-outs, fuses and relays, give quite different results according to whether they are shaken or not. For example, a lead fuse passes through a pasty stage as the current through it is increased, and vibration will bring about mechanical rupture, causing the circuit to open at a much lower current than would be the case if the wire were still. The effect on delicate instruments has been dealt with by Mr. Fleming, but his recommendation of ferro-concrete for a laboratory building is not strongly supported by the present author, on account of the considerable transmission of sound through this material. For this reason, brick construction is to be preferred.

With regard to equipment, the operations involved in development will indicate what is required. These may be classed in chronological order as study and design, model making, and testing.

For the first are required offices with drawing equipment, reading and writing rooms for juniors, and a library provided with an index of literature and information.

The model-making shop does not call for much special comment. Its lay-out resembles that of a tool room, with a lengthwise strip devoted to machine tools. Vibration and noise are minimized, and cleanliness and convenience increased, by adopting individual electric drive for the machines. Provision should be made for wood-working, as it will be necessary to represent in hardwood the porcelain parts of trial designs for the models.

Most of the care and forethought will be expended on the testing laboratories, and these will vary according to the nature of the industry. A description of some apparatus designed by the author for use in switchgear development is given in Appendix 1, together with the machine tools required for this purpose.

IX. Procedure in Development.

Speaking quite generally, the method to be employed for evolving a new product for manufacture in the shops comprises study, consideration, sketching or otherwise indicating the resultant design, making the model according to this or to fuller drawings that may be advisable, and testing the model; followed by modification of the design and re-testing as required, until the desired result is obtained.

No invariable course as to the exact procedure to be followed in the development of every model can, however, be prescribed, as this will vary not only according to the nature of the development, but also according to the personal equation of the investigator. For example, one might be tempted to prescribe study or search for information of a particular kind before engaging in any practical work. Yet it may happen that the preliminary carrying out of a test upon an existing or a simply constructed model may render subsequent study easier and more profitable, owing to the ability thus conferred of visualizing the apparatus and its behaviour, and also owing to the experience so gained in the practical working of the principle involved.

One very important rule may, however, be laid down for general observation. This is a corollary to the

* "Planning a Works Research Organization," *Journal I.E.E.*, 1919, vol. 57, p. 153.

principle, already enunciated, of analysing a problem into its constituent parts and attacking these separately; and enjoins a policy of breaking up a course of development into a series of steps, each representing a difficulty to be overcome, and of performing them seriatim. It is a great mistake to expect a model to demonstrate too much at any one stage, and, except for the simplest pieces of work, the surest and, in the end, the quickest progress is made by constructing a series of models, each achieving some definite result and overcoming some difficulty of design. In some cases entirely distinct models may be required for each stage, and these may be preserved as a record of the procedure at its completion. In other cases the same model may be modified after each test or trial. In others it may be preferable to use two actual models, which are modified alternately, in order that each alteration may be evaluated by a direct comparison of the apparatus before and after this has been effected.

At first sight the above may sound over-elaborate and may appear to threaten undue consumption of time and expense, but this is far from being the case, as may be exemplified by considering the initial step of the series. The first experimental information required concerning a proposal is whether it is practicable or even workable, and the first model should, in general, be made up to demonstrate this. An examination by the various parties concerned may then reveal some fundamental failing that renders further steps unnecessary, and the whole matter can be dropped before any great amount of time and expense has been devoted to it.

For these reasons, no time should be lost and no unnecessary trouble should be taken in getting out this model, which need be neither durable nor attractive in appearance. To secure ease of construction, brass may be used instead of steel or cast iron, and wood instead of porcelain or other insulation, while soldered joints may be employed to obviate screwing, riveting or cottering. Such a model is easily modified as regards details, such as the exact size, shape or position of the parts. It is also just as good as a more elaborate one for demonstrating the worth of the original proposal, and for serving as a basis for the confident production of a more definite and finished design. These points can best be made more definite by the description of typical examples.

One of the simplest examples of development work is the electrical operation of some process or apparatus that has hitherto been actuated by some other means. In such a case the first model would, in general, consist of the original plant, to which the electrical element has been added. After this model has shown that the project is worth proceeding with, the problem would be carefully reconsidered from two opposite points of view. In the first place the reason for the various features of the original design would be analysed, in order to ascertain how these will require or admit of modification when electric operation is applied. In the second place, the advantages that can be conferred by the latter must be checked off, in order that the new design may be such as to utilize these to the full; while its disadvantages must also be realized, to ensure that they are provided against in the new design. Then, and not until then, should work proceed on the next model.

As an instance of such a type of development, the conversion to electrical operation of a belt-driven machine tool, such as a radial drill, may be described. For the first model, the machine tool, motor, and rheostat would each be obtained separately. The motor would be located where it could be easily fixed, e.g. on the floor, while the starter might be screwed on to the wall, or the column of the machine, or mounted on a pillar fixed to the floor. In this form, preliminary tests, such as those upon the power requirements, costs of running, speed control, upkeep of the motor, etc., could be made.

It would next be realized that the machine itself had not yet derived any advantages from the use of electricity, being fitted with a number of complications due to the exigencies of belt-driving upon a pulley at a fixed position and running at a constant speed in one direction. On the other hand, an extra complication had been added, in the shape of a starter placed in an inconvenient situation, i.e. away from the other operating levers, and also requiring more careful treatment than they do. In addition, the installation of such a group is by no means simple, in that locations have had to be found for three separate appliances.

In the next model, therefore, the three components will be combined into a single unified apparatus, which can be set up anywhere within reach of the electric supply and requires only about four fixing bolts and no inter-wiring to accomplish its installation. First, the motor will be mounted on the machine so as to be in a position to drive the actual drill spindle as directly as possible, thus dispensing with all, or nearly all, the usual belts, connecting shafts, mitre wheels and other gearing. Secondly, the control apparatus will be mounted in an appropriate position upon the machine, and endowed with the requisite automatic features to enable it to start and reverse the motor without requiring more careful treatment for the control handle than is accorded to the other handles of the machine. The handle will be so situated as to be convenient to the hand of the operator, i.e. among the other operating levers, if necessary. Thirdly, as much of the change-speed gearing will be dispensed with as possible, by utilizing rheostatic or other electrical speed control, due regard being had to the necessity or otherwise of using the same design of machine interchangeably for alternating and direct currents. Lastly, the complete design will be scanned with a view to simplifying and unifying the combined machine as far as possible, especially with regard to its mechanical details. For example, it may be found possible to utilize the motor as a counterweight to the radial arm and drill-head.

An illustration of a radial driller that has undergone this course of development is given in Appendix 2 (see Fig. 16).

It will be seen that this process is analogous to the life history of practically any fully developed apparatus, such as the electric tramcar or the steam locomotive. The first electric trams were simply horse cars with motors and controllers attached to them; and the early locomotive models were merely stationary engines on

wheels that were geared or otherwise connected to the driving shaft. These old patterns were the first rough models that afforded data for the more perfect types that followed them.

The production of an entirely new design differs from the above only in that the starting point is not provided and has to be decided upon before any positive progress can be made. This first step is the most difficult to describe, since the personality and the originality of the designer play a large part at this stage of the proceedings. Sometimes it is possible to evolve a design entirely original in every respect, while sometimes an idea may be obtained from some existing apparatus, belonging perhaps to a totally different branch of engineering. At other times it is helpful to know how other designers have solved the same problem. The author's opinion is that the latter assistance should not be invoked except as a last resource, for the imagination is at its best when it has a blank page to draw upon. As has already been intimated, however, this part of the problem cannot be done according to rule but must be left to the genius of the individual worker.

In this connection a distinction should be drawn between the study of another worker's solution to a specific problem in hand, and the study of works, apparatus and designs, as a part of an investigator's general training. The latter is in every way excellent in inculcating resourcefulness and a knowledge of designing methods, while the former is a not very "sporting" short cut that may actually prevent an original solution from being reached.

As an example of complete development *ab initio*, suppose that a firm which has hitherto not made contactor gear decides to do so. A member of the department who has had the most suitable previous experience is put in charge of the work and settles down to the problem of producing as original a design as possible for the most fundamental species of contactor. When he has arrived at one that he considers to be worth making up, simple working drawings are quickly got out from his rough sketches and to his instructions; and these are passed on to the model-making shop where, under his supervision, they are put into concrete shape with as little delay as possible.

The model, which at this stage probably bears only a moderate resemblance to the final design, as it must be made up as far as possible without requiring castings or stampings, is now passed into the test room of the department, where its performance is investigated as fully as is practicable. It is given a rough preliminary test to make certain that it functions as desired and that it is good mechanically. Its exact performance is then recorded in the form of curves connecting coil ampere-turns and pull-in distance, ampere-turns and spring pressure, etc. Defects made evident during this examination are reported and corrected either by modifying the original model or by the construction of new ones. The capabilities as represented by the test curves are studied and compared with existing standards, with performances of existing apparatus, and with the duty required. When the model passes muster according to these criteria, it is handed over to the works drawing office.

Here full working drawings for the final model are got out, in conformance with the data thus supplied, the design being now especially adapted to the manufacturing practice in vogue in the particular shops to which the department is attached. The intention is that the finished product shall be made in the factory from these drawings, but, before this, one model is made from them in the development workshop to check the correctness of the design. This model is given a final test, a set of coils is got out for it to suit the various voltages at which it is to work, and these are, if necessary, given heating and working tests.

The same process is then carried out with regard to the master controller, relays and interlocks that go to make up contactor installations. Finally, a complete set is assembled and connected to a suitably loaded motor, representing the most exacting duty that the apparatus will have to fulfil, and this installation is given an endurance test under working conditions. Again, any defects that manifest themselves are made good, and the tests are repeated until complete satisfaction is given, in which case the development of this particular model is complete and the shops and drawing office are notified that manufacture may go forward.

This procedure is representative of the most usual work of such a department, namely the complete development of a product, and it also sufficiently illustrates the development of a new part in an existing apparatus, or the mere improvement of the latter. In a certain proportion of cases, however, the design for a new article is evolved in the drawing office, and thus full working drawings are supplied to the development staff. The latter portion of the process just described, consisting of making up the model, testing it, amending the design, and re-testing, is then gone through, unless the last two steps are found to be unnecessary. The drawings are then returned to the drawing office, together with the model and a report detailing the tests and modifications that have been made, as well as comments and suggestions.

X. Recording and Filing of Results.

In order that conclusions that have been reached or information that has been evolved as the result of research work may be preserved and distributed to those interested in the particular subjects dealt with, an organized system of recording results is essential. It should be so arranged that the whole of the results are kept on record, in such a form that reference may be quickly and conveniently made to them by all who require to do so, without the possibility of ambiguity or misunderstanding as to any detail.

The most valuable information is usually that derived from a test, as it involves the expenditure of the greatest amount of time, trouble and expense in its acquisition. A large proportion of tests are made upon a sample or model supplied or lent for the purpose, and these cannot be duplicated without considerable trouble and delay. Many others involve the destruction or consumption of costly apparatus or material. It is thus natural that special care should be taken in the preservation of test data. A scheme will therefore be described whereby this species of informa-

tion is adequately cared for from the receipt of the inquiry to the completion of the final report upon the investigation.

There is a temptation evident in test rooms to enter figures and details relating to investigations upon loose sheets of paper, the after career of which is, to say the least, precarious. A better method is to record the data in note-books which are carefully retained, but even these form in the course of time effective hiding places for the information entered therein. Some special scheme is therefore desirable.

The system employed by the author makes use of a small number of loose-leaf binders, in which blank sheets are clipped in readiness for an investigation. When one of the latter is begun, a binder is allotted to it, in which are inserted concise instructions, together with any correspondence or other data bearing upon the matter. Full notes, test figures and other relevant details are then entered upon the blank pages, as they are arrived at. This entails that every detail of the apparatus, conditions and circumstances that may be of importance in, say, 10 or 50 years' time, must be included. No reliance must be placed on the memory of any participant, but every fact must be recorded on the assumption that it will be forgotten as soon as the piece of work is completed.

After a final result has been reached, and also, if desirable, at intermediate stages, an official report is compiled from these notes. Such reports serve the double purpose of placing the proceedings upon permanent record, and of acquainting any number of interested persons with what has been done. It should therefore be dictated to a stenographer, who can type any desired number of copies. The original notes are then removed from the binder and clipped into a folder, which is clearly labelled with the serial number of the report and a title briefly describing the nature of the investigation. This can now be filed away in a suitable cupboard. One or more copies of the reports will also be filed in the office of their compiler.

At first sight it may be thought that the notes and the reports contain the same matter, and that therefore it is not necessary to file both versions. This is not the case, however, as for several reasons the reports will not form an entirely sufficient record. First, the reports, being intended for frequent use by a number of busy men, must be made concise and readable. If they were only to be kept by those concerned in the investigation for reference purposes, they might then contain full details of all proceedings, such as the complete particulars as to tests made, and a full set of the readings taken during such tests. But since many of those who read them are interested chiefly in the results and require these to be in as lucid and graphic a form as possible, only the significant portions are included. This will nevertheless be sufficient in the great majority of inquiries. Secondly, a proportion of the proceedings are not worth placing officially on record. It is usually the case, for example, with all but the simplest tests, that one or more trial experiments are made before useful results are obtained. These serve to indicate definitely the precautions that have to be taken, and any refinements that have to be effected in the proposed method and apparatus. Results of a kind are obtained and these should certainly be kept, but they are not worth circulating. Thirdly, there is always the possibility that some part of the result may seem unimportant when a report is compiled, and hence may be omitted, but it may subsequently become significant, or a recorded result may be challenged and may require verification from the original notes.

Since the original notes must therefore be preserved, a test report should contain only a brief description as to the method employed, and a comparatively full description of the results, omitting, however, tables or figures whenever these can be satisfactorily replaced by curves. The conclusions drawn from the test should be given in detail, together with comments and recommendations. The matter should be preceded by an introduction giving the reason for the investigation and referring to any circumstance which has led up to it, and by a sufficiently detailed description of the apparatus, component or material experimented upon. It is an advantage to add to the front of the report a page upon which is a very short summary of the introduction and conclusion. This only may be supplied to those who are less intimately concerned with the matter, for their complete file, in order that they may be acquainted with the bare results and may be able to ask for the whole report if they desire it. It also serves to inform a searcher as to the contents of the report, and will thus frequently save useless perusal of the report itself.

While these reports should be concise, they should not be so abbreviated as to form a one-sided record. There is so much more temptation to dilate upon those results which are "according to plan," that the importance of others indicating failure or disappointment is often overlooked. It should be remembered that there are two limits to every phenomenon, the upper and the lower, and it is just as necessary to know the one as the other. It is therefore necessary to place on record both what cannot be done as well as what can be done, and a failure may, in consequence, be of even greater importance than a success.

XI. Indexes of Literature and Information.

An important requisite for a research department is a means to enable an inquirer to ascertain quickly what information is available upon any desired subject in current literature, and where such information is to be found. This is achieved by the aid of one of the many types of index. The author proposes to describe two of these, both of which were especially designed for aiding electrical research work. They differ in the amount of labour required in their formation, and in the amount of assistance they afford to the inquirer. The first is most appropriate for a comparatively small staff, and the second for a larger one.

The simpler scheme was designed six years ago by the author for his own department, and has since continued in use without alteration. In this case the aim has been to indicate the nature, extent and whereabouts of all information relative to switchgear, contained in the books and periodicals actually accessible in the building. All but 5 per cent of the work entailed

can be performed by a junior, or even an intelligent office boy. Each entry consists of a single line on a specially designed index card. No attempt is made, beyond about six words by way of title, to reproduce any portion of the text, but the aid of tabulation has been invoked to record compactly the value as well as the location of the abstract.

TABLE 1.

Specimen of Card for Simpler Index of Literature.

SUBJECT: Research — No. 1

PUBLICATION: Journal I.E.E.

Date	Vol.	Page	Matter or Title	Pp.	Ills.	Author
Apr. '13	50	306	Aims, &c., Internat. Electrotech. Comm.	20	0	Thompson
Apr. '15	53	799	Plea for Sc. and Tech. Commsrs.	3	0	Digby
Dec. '16	55	37	R. and Future Sources of Energy	4	0	Robertson
Feb. '19	57	153	Planning a Works R. organn.	39	25	Fleming
Oct. '20	57(s)	134	Coordn. of R. in works & labs.	23	0	Constantine
....	..	...	....	..	..	....

An example of the cards employed is given in Table 1. There are seven columns on each, of which the widest is for the title of the article, or, if this is not sufficient for identification, the matter is indicated in five or six words, the dimensions of the cards being 5 in. by 3 in. The first three columns enable the precise volume or number to be selected and the page to be found, while the date and the last three columns indicate the probable usefulness of the extract. It will be observed that the latter need not have been previously read.

With regard to classification, a list of subjects to be indexed was first got out, and a guide-card set apart for each. Distinguishing symbols of one, two or occasionally three, letters were allotted to these, and an alphabetical arrangement of the symbols determined the order of the subjects in the index. For example, "B" denotes switchboards generally, "BD" distribution boards, "BT" truck-type switchboards, "F" fuses generally, "FC" cartridge fuses, "R" research, "RH" rheostats, "RL" relays, and so on.

Extracts from one publication only are entered on any one card, a rule convenient not only for reference, but also for the work of compilation. The latter is best done from the complete volume. A junior goes carefully through the volume index, observing the references to the subjects on the prepared list. He finds all these places and marks them with strips of paper. The completed volume is then handed to a senior member of the staff, who glances rapidly through it, and removes the markers from these extracts that are not worth indexing. This done, the work of entering is carried out by the junior.

A more elaborate system, in which a short summary of each extract is filed on the actual cards, has been designed by the staff of the General Electric Company's research laboratories at Wembley. A separate card is employed for each entry, and two kinds of guide-card are used, "third-cut" for the main subjects and "sixth-cut" for the subdivisions.

A specimen of these cards, the dimensions of which are 6 in. by 4 in., is shown in Table 2. The manner in which the headings in the left-hand top corner are set out will first be noted. These are in several lines, of which the first is the heading on a main guide-card, and the second that on a "sixth-cut" guide. The remaining lines are intended to amplify the indication already given as to the contents.

Further amplification is afforded by the précis occupying the lower half of the card, which may contain up to 80 words. It may be compiled from the actual article or other extract while this is being read, but in the majority of cases there will not be time to do this,

TABLE 2.

Specimen of Index Card Containing Précis of Subject Matter.

> Dielectrics—Porcelain. RIDDLE, F. H.
> Thermal props.
> Composition, effect of.
> Thermal expansivity.
>
> Chem. Abs. Vol. 14. 1. pp. 106, Jan. 10, 1920.
>
> J.Am.Ceram.Soc. 2 804–11 (1919), cf. C.A. 13 3298.
>
> Bodies high in clay show low thermal expansion, and variations in flint for such bodies show no decided effect. As the clay content is lowered and the amount of quartz increases, its quantitative effect becomes more marked. Replace quartz by inert material lowers the expansivity. Calcined kaolin may be effective as sillimanite or other synthetic silicates. 399

and the help of published extracts, such as *Science Abstracts,* is then invoked. These will, in general, be too long for the present purpose, and not more than the 80 words are then underlined by the indexer and are copied onto the card by a typist. The practice at Wembley is to put each subject in the hands of a member

of the staff, who is responsible for keeping the index up to date in this particular respect.

The other entries on the card give the author or authors in the top right-hand corner, the references to the volume of abstracts from which the précis is compiled, and the reference to the original publication containing the extract.

Besides the subject index as described above, a duplicate set of cards is also filed according to the authors, as a search for information is frequently most easily carried out by referring to a list of publications by certain writers who are specialists in the subject of interest.

In addition to current literature, information from any other source may be filed in this manner. Test-results, patents, verbal criticisms or interviews, contents of letters, and other matter may be inscribed directly upon the cards, if the length be not too great. Otherwise the file in which it is given at length is indicated.

Card indexes are also invaluable for keeping a record of work done, by the allocation of a card to each problem and the noting of each step thereon. Ideas may also be jotted down on index cards as they occur, and filed for future use. Test-results may be tabulated on a small set of cards. The progress of patents taken out by the department, business addresses, serial numbers of reports, and lists of patterns, drawings and diagrams, are other examples of the many uses of a card index in a research department.

XII. Industrial Research Organizations.

Industrial research is carried on by a few private individuals, by firms of consultants, by universities and colleges, by manufacturing firms and by research associations. In view of the interesting and substantial improvement that has taken place in the research situation during recent years, a very brief reference will now be made to these various spheres of activity.

Owing to the change in industrial conditions referred to in the introduction, the private worker is at a greater disadvantage to-day than formerly, unless he is possessed of independent means or confines himself chiefly to philosophic research. Not only are the difficulties attending tests and experiment much greater than in the early days, but the advances in the various applied sciences are more rapid and it is not easy to maintain touch with these unless the worker is attached to a firm or other association. When a private experimentalist has developed a useful design, the further difficulty occurs of selling the results of his work or otherwise securing its adoption in practice, since firms which maintain their own research departments naturally expect them to produce as many of their new models as possible. Individual members of the staffs of electric power companies or departments, and similar organizations, frequently develop new apparatus, the patent rights of which firms are glad to purchase. These workers are in an especially favourable position in this respect. Other private inventors will probably find their cases provided for to an increasing extent by the associations established under the ægis of the Government, concerning which more detailed reference will be made below.

It is strongly maintained by some authorities that universities and colleges should not engage in any but purely philosophic research, since the prosecution of the latter is most essential and academic institutions are the proper places for this. If they are tempted to take up industrial research, university investigators will be attracted from their legitimate field by the greater emoluments that are expected to be available for utilitarian work, to the grave detriment of pure research. It is also considered that a teaching institution may not be sufficiently in touch with practical conditions to do such work effectively.

While the above opinion should not be entirely disregarded, there is no doubt that a certain amount of industrial research can and should be performed at such institutions. There are many reasons for this, of which the most direct is derived from the valuable industrial investigations that have already been carried out at many of our colleges and universities. It should be the aim of every one of these to foster a spirit of research in its students, and this is most effectively done, in an applied science department, by instituting researches in applied science. Perhaps the strongest reason of all is the great need for a closer degree of contact between the universities and the industries, for the advantage of all concerned. This is attained by anything that brings them together in the mutual endeavour to solve some pressing problem.*

The author has come into personal contact with the work now being carried out at Sheffield University in the furtherance of these various aims. Special members of the staff have here been appointed to direct research, and do not have to undertake any routine teaching. The authorities are also willing to provide the necessary facilities and staff for the performance of any industrial research that may be desirable. The work of the Fuel Technology and Mining Departments upon the safety of electrical ironclad apparatus from internal explosions may here be mentioned with appreciation. In another research undertaken in conjunction with the electrical industry it was found possible to secure to an important extent the assistance of the city electricity department. Such a comprehensive degree of co-operation cannot but excite the greatest satisfaction among those interested in electrical engineering development.

A similar type of co-operation, between the Physics Department of Canterbury University College, N.Z., and the Testing Department of the Lake Coleridge Hydro-electric System, was responsible for the solution of a most troublesome difficulty in connection with 66 000-volt transmission line insulators.†

Prior to the war, organized research was carried out by comparatively few firms in this country, although the beneficial result of their enterprise has long since been evident. The pre-eminent position of the British cutlery trade would scarcely have been possible, for example, without the research work of Hadfield and others. More recently, the vital need of developing quickly our own products in many branches of industry has led to the wide establishment of such departments, further instances of which need not be quoted.

* See Karapetoff: "Suggestions for Electrical Research in Engineering Colleges," *Journal of the American Institute of Electrical Engineers*, 1916, vol. 35 (2), p. 895.

† See C. C. Farr and H. E. R. Philpott: "Test and Investigations on Extra High Tension Insulators," *Journal of the American Institute of Electrical Engineers*, 1922, vol. 41, p. 711.

Many, if not most, items of industrial research are such as to benefit every firm engaged in a given class of manufacture, and would be most economically carried out by co-operative associations serving the needs of whole industries. The provision of these through the good offices of the Committee of the Privy Council for Scientific and Industrial Research constitutes one of the most welcome items of industrial history that has been enacted within recent years. Formed shortly after the outbreak of hostilities, the Committee issued their first annual report in the middle of 1916. In April 1918 they took over from the Royal Society the maintenance of the National Physical Laboratory, and with it the responsibility for much of the research work in connection with the war, a staff then numbering over 500 being engaged on such research. In addition, they drew up a scheme whereby research associations were to be formed in the various industries, and they stimulated the establishment of these. The result has been the existence at the present day of a large number of these organizations, actively engaged in work which has already borne abundant fruit.

By the middle of 1918 some 30 industries were in process of forming research associations, of which three, including the British Scientific Instrument Research Association, had already been licensed by the Board of Trade. The British Electrical and Allied Industries Research Association began operations shortly after this date, under the direction of Mr. E. B. Wedmore.* In addition, specific researches, e.g. those in fuel, mine rescue, tin and tungsten, timber, building materials, and industrial fatigue, were instituted and placed in the hands of special research boards.

Besides acting as an organizing body, the Council has been the medium for the subsidizing of research by the Government. The cost of the various researches is partly borne by the industry and partly met by these subsidies. For example, the investigation concerning the production of tin and tungsten in Cornwall was first conducted with the aid of a grant from the Institution of Mining and Metallurgy. The Research Department also assisted with a grant, but when it was evident that work on a larger scale was justified and desirable, they made it a condition for the continuance of financial assistance that the locality should take a more active part in the work. In a short space of time, subscriptions to the extent of over £2 500 were guaranteed by the principal mine owners and landlords in Cornwall for a period of three years, whereupon a similar amount was granted from the Government funds.

The general policy of the Department, which has remained unchanged since it was formulated in the middle of 1917, is the appointment of a responsible Director to organize each group of researches, assisted by an advisory board of distinguished men of science. The important fact has been recognized that "research work, like other forms of creative activity, will not flourish under committee rule."

The above brief notes may serve as an introduction to the subject for those who have not hitherto come into contact with these developments. Full particulars as to each year's progress may be obtained from the annual reports, published about the end of August by H.M. Stationery Office. These records of a movement that promises to be epoch-making in its scope and its results, are well worth perusal.

* See "Institution Notes," *Journal I.E.E.*, 1921, vol. 59, pp. (14) and (23), and 1922, vol. 60, pp. (3), (14), (22) and (27).

XIII. Co-ordination.

Pioneer work of any kind is exacting in its requirements as regards both talent and finance, and it is therefore important that the fullest practicable co-operation should be maintained among those engaged in such work. The organization for effecting this will, however, be very different from that appropriate to routine occupations, for which the various participants have merely to be directed along well-tried routes. For research, there are available no pilots familiar with the course, and hence sailing orders of the most general description are alone possible.

A scheme was proposed about four years ago in a paper* read before this Institution, whereby every research worker, whether in a public, university, or works laboratory, would work to the instructions of a controlling staff appointed by the Government. This staff would be partly centralized, and would consist partly of travelling inspectors whose principal functions, to put the matter quite bluntly, would be to decide for every research worker in Great Britain exactly what he should investigate, invent or discover, and to see that he did it.

This scheme, in the opinion of the present author, is merely the ordinary organizing system as employed in the Army or public services, with the research workers inserted in the lower grades. It would certainly introduce an atmosphere that would stifle research, while any benefits which it might be able to offer would be forwarded by such ponderous machinery and by such devious routes that their arrival could not fail to be tardy.

Between terrestrial and scientific exploration there is a close parallel that will assist in indicating the nature of the co-ordination required. The workers in the former may be grouped under the three headings of explorers, pioneers and prospectors, closely corresponding to the three-fold division of research workers. The very word "research" is merely "search," with a frequentative or intensive prefix to denote thoroughness.

One notable example of terrestrial search, that for gold, has from the earliest times been carried out with all the energy and resources, scientific, executive and commercial, of which mankind has been capable. Yet no comprehensive organization has ever been found possible among the gold-seekers, whose methods have been characterized by individual freedom and enterprise, and whose driving force has simply been the quest itself.

No difficulty is experienced in deducing the co-ordination needed in this case. It is that the results of all other searches should be easily available to every worker, especially those in his own vicinity. Thus the great requirement is a co-ordination of results, and this holds good whatever the object of the search may be. In the case of electrical research this need is being largely

* See H. R. Constantine: "Co-ordination of Research in Works and Laboratories," *Journal I.E.E.*, 1919, Supp. to vol. 57, p. 134.

supplied by the work and publications of this Institution, by sister societies at home and abroad, and by the technical Press. *Science Abstracts* forms one of the most efficient agencies in bringing about co-ordination among electrical research workers, while the abridged specifications issued by the Patent Office, and other publications of a like nature, assist still further. During the war the Government wisely provided a similar means of co-ordination for general use on the lines of *Science Abstracts*, by beginning the publication of the *Technical Review*. The valuable work done by the Electrical Research Association in compiling exhaustive précis of available information on various branches of electrical engineering has assisted co-operation in research in the most effective way possible.

Any useful advance in co-ordination can be effected only by a development along the above lines. For example, a central inquiry bureau might be instituted, or a complete and comprehensive card-index might be worth publishing, either of which might render available any possible information. This information should include as far as possible a record of what has not been done, whether as a result of failure or of omission; and means might be found to stimulate efforts to remedy such deficiencies. Indeed, the latter is no new attitude on the part of the Department of Research as far as well-known firms and even well-known individuals are concerned, but it is not yet accomplished generally. In the same manner, advantageous co-operation between individuals, firms, industries and countries, already brought about to a certain extent by the present organization, will be capable of yielding enhanced results as the outcome of further thought and experience. The establishment of "cross-connections" between various industries is a function fraught with big possibilities.

In particular, co-operation in research between different parts of the Empire will be especially prolific in results. The colonies have in the past accomplished notable successes in the development of industry, and are capable of further achievements in the future. In some branches of industrial research, by far the most favourable fields for work are in the Dominions; for example, the application of electricity to agriculture and non-ferrous metallurgy; the development of electrochemical and other industries requiring very large quantities of cheap electric power; hydro-electric generation; and e.h.t. transmission. A greater interchange of research workers between the Motherland and the Dominions would yield most valuable results from all points of view.

XIV. Conclusion.

An endeavour has been made in the paper to assist the carrying out of the more technical variety of industrial research work usually known as "development," for the benefit of the electrical engineering industry. The line of demarcation between the functions of the various kinds of research workers is not always sharply defined, and it is not desirable that it should be so. Consequently, much of the treatment has been made general, to cover a somewhat wider scope than that included in development pure and simple. It is the author's confident hope that the increasing use of research, especially when carried out in association with the manufacturing staff, will continually increase the successful application and the prosperity of our industry, and will raise it to a dominating position among the achievements of other nations.

The author would like to express his indebtedness to his assistant, Mr. F. R. Combes, B.E., for his valuable help in preparing the illustrations for publication.

APPENDIX 1.

Equipment for Switchgear Development.

A short outline of some items of equipment utilized by the author in the development of switch and control gear is appended. These are grouped under the headings of testing outfit and model-making appliances.

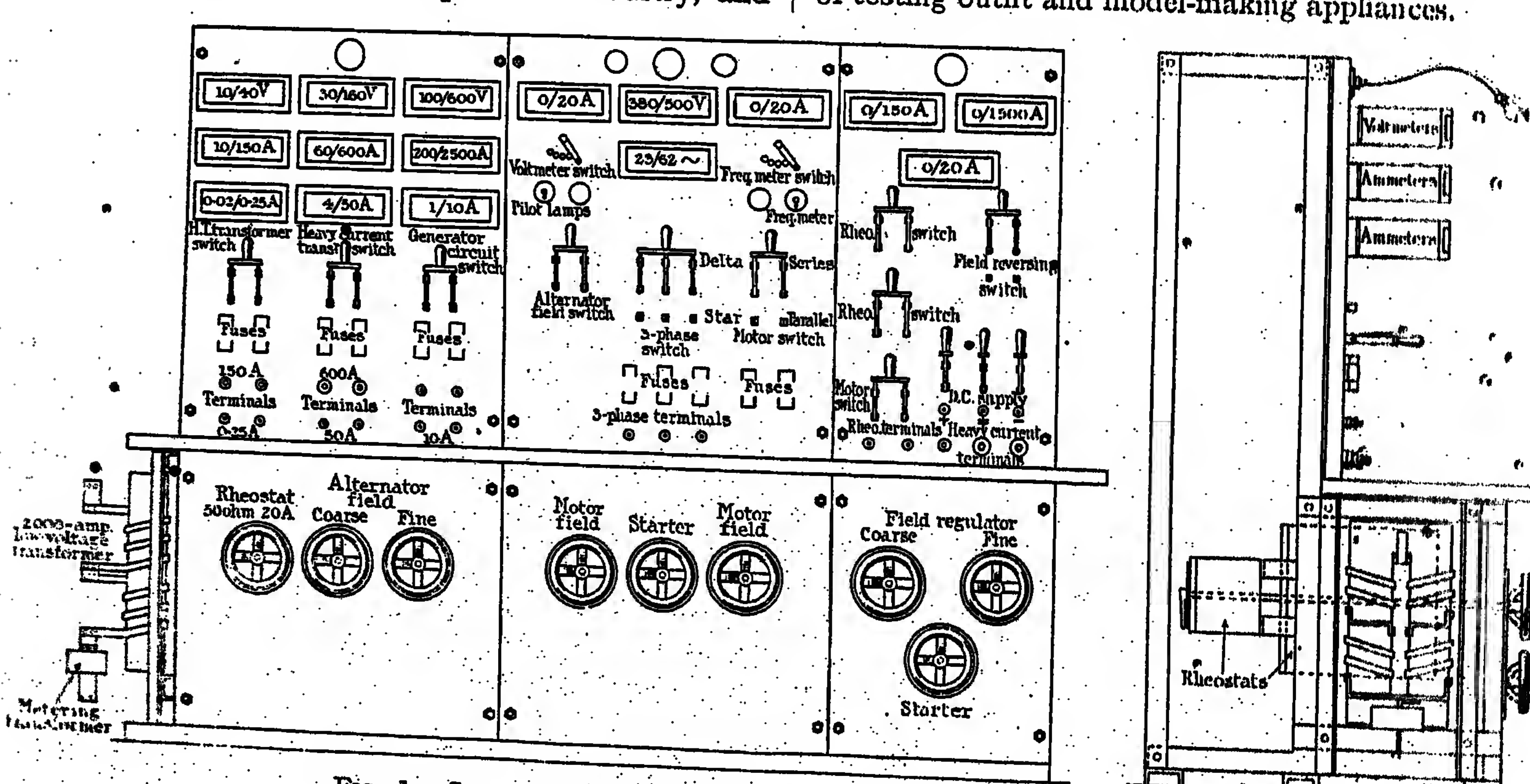

FIG. 1.—Combined test-board and bench for electrical development.

The first requirement for testing is a supply of power for operating the various pieces of apparatus undergoing test. This is effected by two motor-generator sets for direct current and alternating current respectively, controlled by the switchboard shown in Fig. 1. There are only the two machines in the d.c. set, the generator giving a maximum of 10 volts and 1 000 amperes, but the a.c. set has two motors which may be connected in series or parallel, in order to render available a wide range of periodicities from the alternator. The latter has both ends of its three-phase winding brought out, and these may be connected in star or delta. The a.c. set gives a normal maximum of 11 amperes at 500 volts, but the current may be stepped up to 2 000 amperes (single-phase) by a heavy current transformer, and the potential may also be raised to 50 000 or 100 000 volts for insulation testing by a potential transformer in a special enclosure (not illustrated). Ordinary d.c. loads are obtained direct from the supply mains.

In the board illustrated, the correct positions for apparatus under test and for test appliances have been

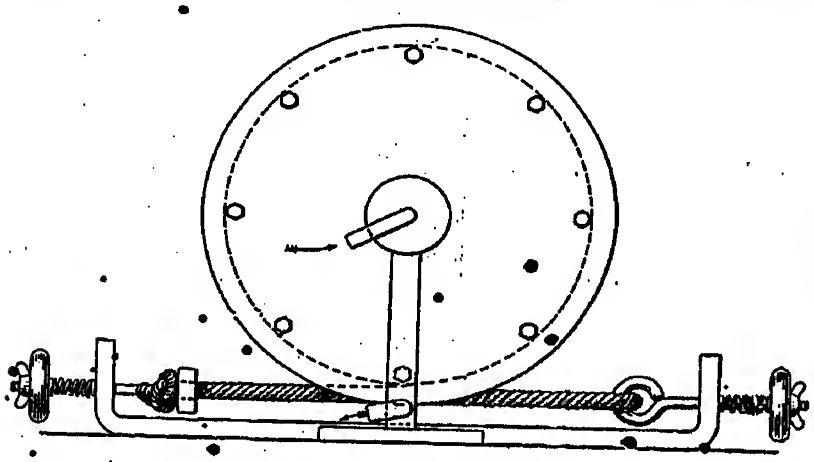

FIG. 2.—Rope brake gear for testing motor, with improved "dry" water-cooling arrangement.

secured by combining the bench with the switchgear. As will be specially evident from the end view, the former divides the upper panels supporting the meters, switches, fuses and terminals, from the lower panels, on which are the controlling hand-wheels, this portion being stepped forward of the rest in such a way that the rheostats are accommodated almost entirely under the bench itself. By these provisions everything is arranged in its most convenient position, and the crossing of the floor by cables from the board to a separate bench is obviated, and with it the feature of the more usual testing equipment that is the most conducive to untidiness and disaster.

Each ammeter is connected in circuit with its appropriate terminals, and thus one only is in use at a time. Double potentiometer rheostats are used for both generators, giving fine gradation over the complete voltage-range from zero to maximum. The heavy current transformer is at the left-hand end of the bench, where the thick low-voltage conductors can be kept short. In addition to the three switches and terminals connected directly to the d.c. mains, there are two double-pole switches and special terminals connecting the mains in series with one or both of the two largest rheostats already on the board. The pilot lamps are intended to illuminate both the bench and the board.

When a piece of control gear is to be tested, a suitably loaded motor is necessary. As far as possible, the author develops gear of this description for a 5 h.p. motor, and two of these, alternating and direct current respectively, are permanently set up, with a water-cooled pulley and rope brake in position, suitable for forward and reverse rotation and rapid adjustment of load. Rolling-mill control is represented by a 40 h.p. d.c. series motor, and by an induction motor of about the same capacity, the brake gear for both of which is shown

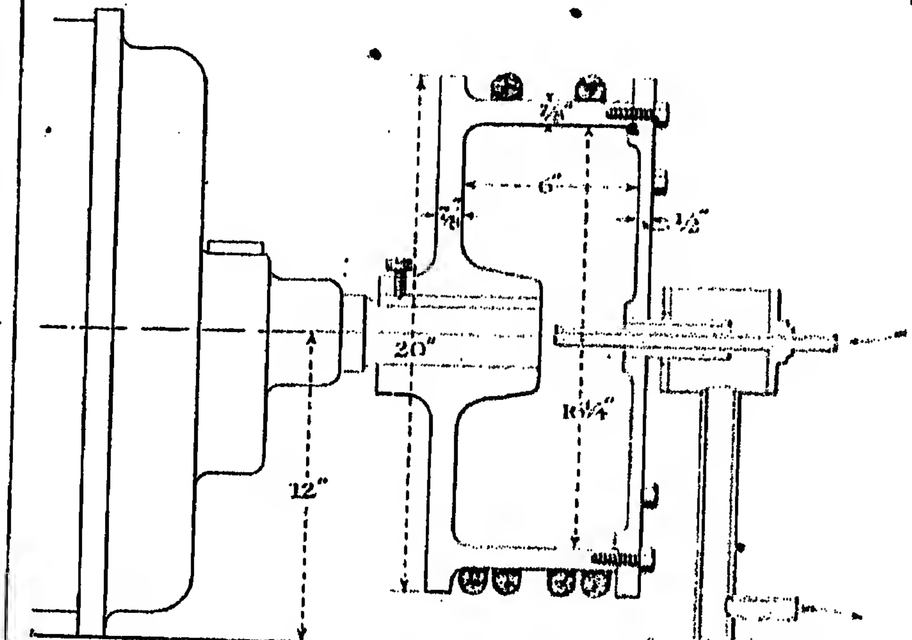

FIG. 3.—Section of pulley and water-circulation arrangement shown in Fig. 2.

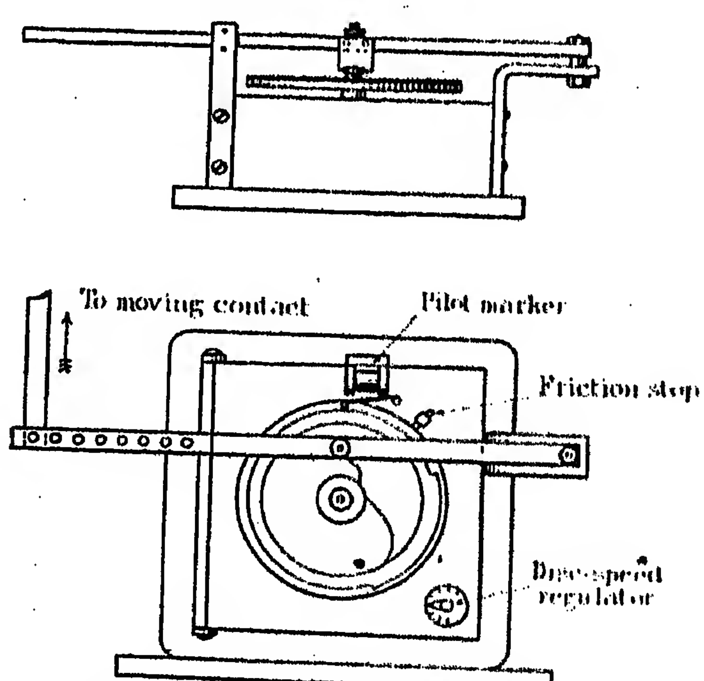

FIG. 4.—Simplified disc apparatus for measuring speed of oil switches.

in Figs. 2 and 3. It was extremely important that there should be no leakage or splashing whatever in connection with the water-cooling, and this was fully accomplished by the arrangement shown, which was specially developed for this purpose.

As will be seen from Fig. 3, the pulley is entirely enclosed, with the exception of a spout of about 1 in. in diameter. A smaller tube passing through this introduces the cold water, and the hot water overflows through the spout, from the ends of which it is thrown into the cowl. Thus it is all collected without any

possibility of splashing or leakage. About 2 quarts per minute are sufficient to dissipate 40 h.p. without quite reaching boiling point.

The smaller pulleys for the 5-h.p. motors are partly open on the outer side, the water being inserted at intervals by means of a filler and allowed to boil away. This simpler method is not safe for the larger pulleys, owing to the higher centrifugal pressures which occur in the water and cause suspended ebullition.

One of the most frequent measurements that have to be made is that of the speed of break of oil and other circuit breakers, and the closing time-lag of electrically operated switches. This was at first effected by the method already described* by Dr. C. C. Garrard. Later, the more self-contained and portable apparatus shown in Fig. 4 was made up, and has given complete

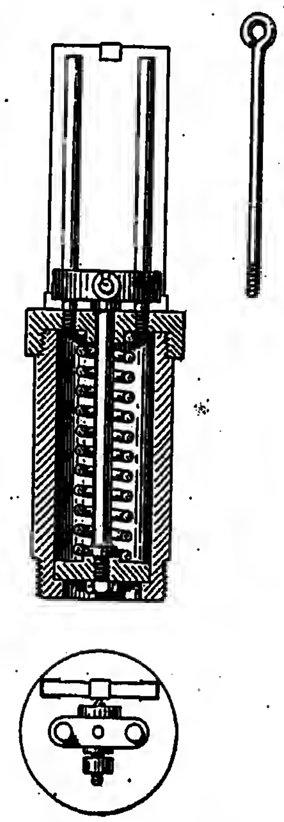

FIG. 5.—Pressure indicator for explosion tests.

success. A clockwork gramophone motor driving a 12 in. disc at a definite speed has been substituted for the drum, electric motor, and tuning-fork timing gear. A convenient part of the moving switch-contact is connected by a rigid rod to a suitable point on the moving arm of the recording apparatus, and the switch is operated when the speed of the disc has become steady. It is then an easy matter to plot the true curve of operation, similar to those given by Dr. Garrard, from the trace on the disc.

Ironclad apparatus for use in mines requires to be tested for resistance to explosion, and this is carried out by igniting in the enclosure the most explosive mixture of air and either pentane or methane, and surrounding the apparatus under test by the most easily ignited mixture of methane. A record of the crest pressure reached is simply obtained by means of the recording gauge shown in Fig. 5, which is screwed directly into the top of the casting. The piston, rod and crosshead are lightly made in aluminium, and a small graphite pencil on the crosshead marks the movement against the spring pressure. The gauge is calibrated by screwing a special eyelet on to the crosshead and directly pulling the latter by means of a spring balance until the pencil once more reaches the crest mark.

The need was felt for a simple apparatus for enabling small samples of switch oil to be flash-tested, and that shown in Fig. 6 was designed and used for the purpose. The electrodes are supported in an ebonite "cage" which can be removed from the small glass vessel for calibration. An ordinary "feeler" thickness gauge, or even a single steel plate 0·007 in. thick, is used for adjusting the separation of the spheres.

Turning to model-making equipment, the machines required for a department of small to moderate size are given in the following list. They are arranged approximately in the order of their importance, and the

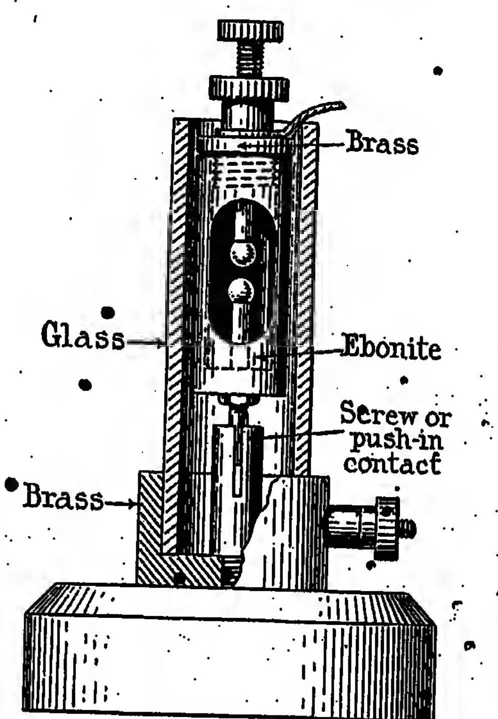

FIG. 6.—Apparatus for flash-testing small quantities of oil.

list thus indicates roughly the order in which they would be procured in the case of gradual growth from a small beginning.

Lathe, 6 in. centres, surfacing and screw-cutting.

Drilling machine, pillar type and lever feed, with ¾ in. spindle.

Grinder, to take up to 8 in. wheels.

Miller, small horizontal, with vertical attachment.

Shaper, with about 18 in. stroke.

Radial driller, with about 36 in. arm.

Small precision lathe, 4 in. centres.

Sensitive driller, high speed.

Brass workers' lathe, 6 in. centres, for rough hand work.

This whole equipment will be suitable for a staff of up to 10 or 12 model makers, in addition to the foreman, one or two labourers and two or three boys. It is supposed that the small amount of woodworking is machined on the metal-working apparatus, a course that has no marked disadvantages. It is also assumed that extra large work is sent to the main shop for planing and other machining.

* "Switchgear Standardization," *Journal I.E.E.*, 1918, vol. 56, p. 226.

APPENDIX 2.

Illustrations of Development.

As it may be of interest to make the remarks in Section IX on "Procedure in Development" as definite as possible, a few examples of the evolution of a new piece of apparatus are now described. It is typically the case, however, that a problem loses much of its interest when the solution is known. This is especially

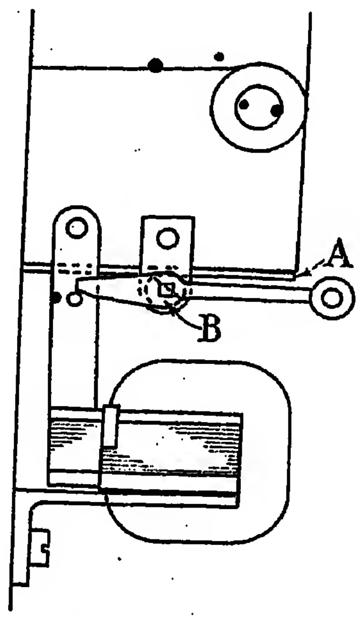

Fig. 7.—First stage of a low-voltage release.

so with the design of apparatus, for the fully developed product is almost invariably simpler than when in an intermediate stage. The great requirement is, in fact, to evolve as simple a solution as possible, and for this reason the final steps consist largely of the

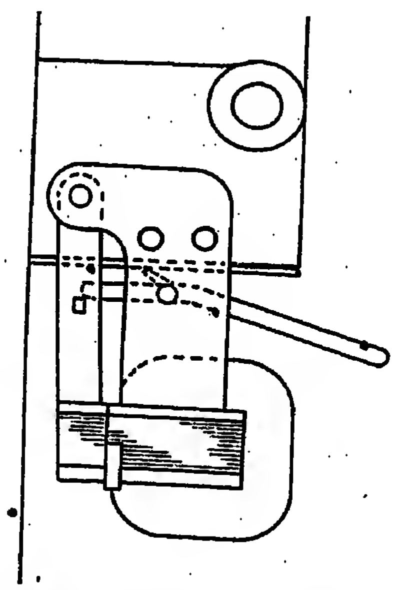

Fig. 8.—Second stage of a low-voltage release.

cancelling-out of complications. As a consequence, the result of the process is a comparatively commonplace article, exhibiting no trace of the lengthy and roundabout course by which it has reached its final state, which indeed appears to the onlooker to be the obvious answer to the original proposition. Yet it is probably true that the simplification of existing apparatus, methods and calculations, is more required at the present time than the production of new ones.

The above consideration renders it a somewhat difficult matter to choose examples of development

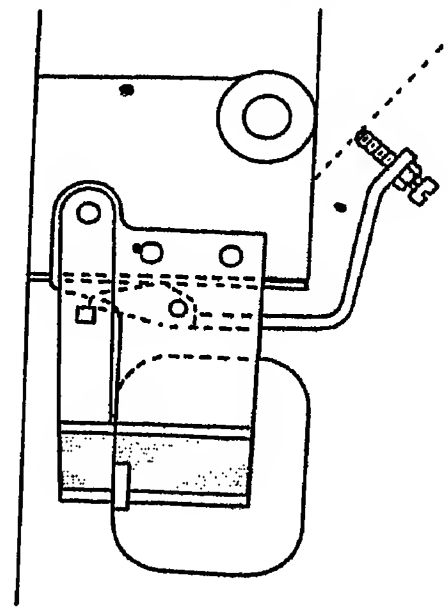

Fig. 9.—Final stage of a low-voltage release.

that are convincing without involving tedious description. The author hopes that this will excuse the apparent triviality of the three that have been chosen.

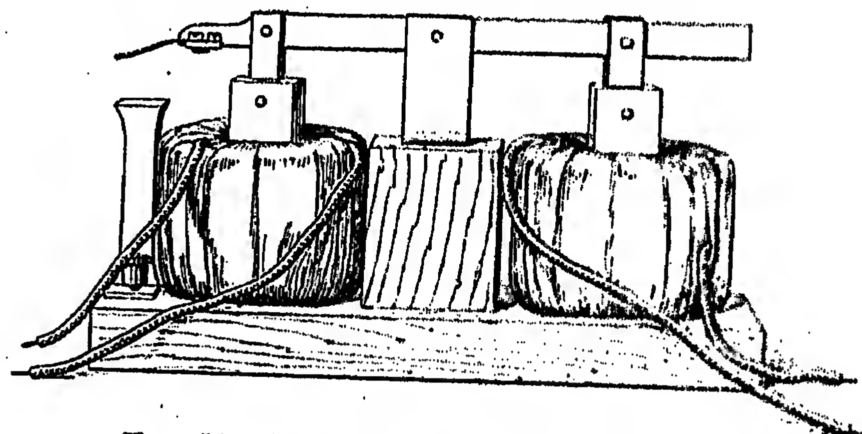

Fig. 10.—First model of a protective relay.

The first, shown in Figs. 7, 8 and 9, is a low-voltage attachment for an a.c. circuit breaker, the moving arm of which is held in by the spring plate, A. Tripping is

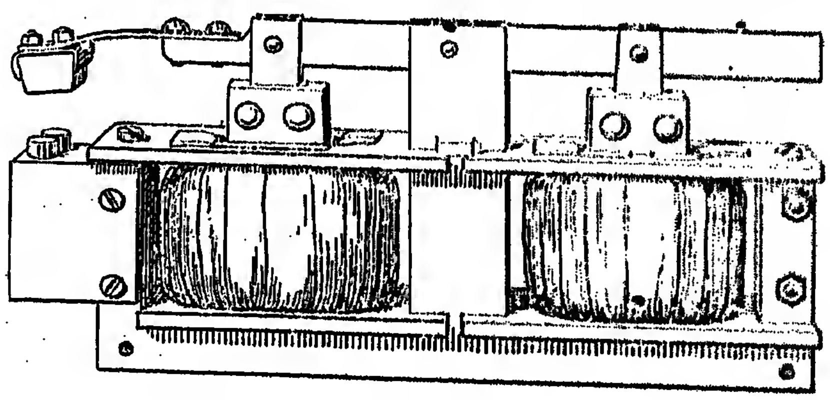

Fig. 11.—Second model of a protective relay.

effected by depressing this plate by 1 or 2 degrees, and when such a release is fitted the spring is given an original set downwards, but is kept up and in engagement by the attachment. Three different designs had been

completed, and had been unsuccessful, before the breaker was taken over, and the figures show three stages in the evolution of the fourth and successful design.

As a result of thought devoted to the problem, the idea was arrived at of forcing up the spring plate by a shaft, B, that could execute a partial rotation, but which would release the spring when a flat formed

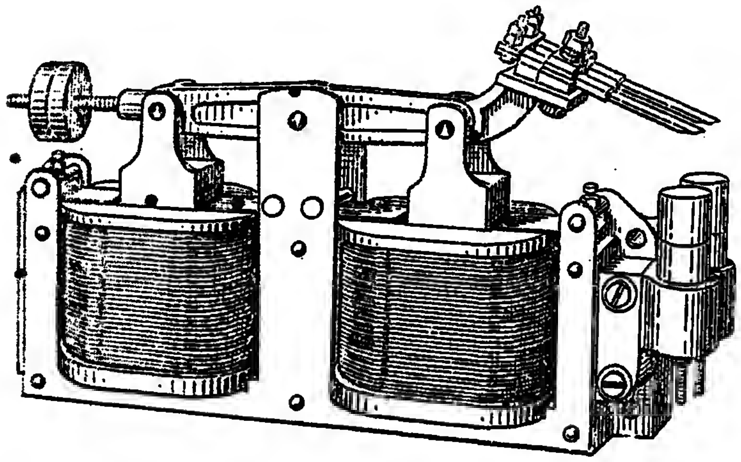

FIG. 12.—Final model of a protective relay.

in the shaft was allowed to move into parallelism. It was supported in the "on" position by two levers, the ends of which rested on a cross bar attached to the hanger of a laminated armature, which was attracted and held in place by an electromagnet.

The first model, as shown in Fig. 7, was made up with the three components independently supported, and this was modified as regards dimensions, windings, and so on, until satisfactory operation was given. In this form the release required to be set by hand after each opening of the breaker.

The principle having been shown to be a practical

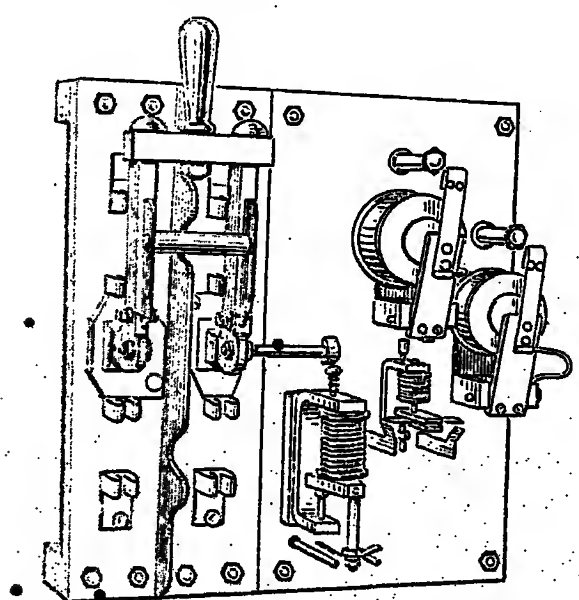

FIG. 13.—First model of an automatic reversing starter.

one, the design was unified by the contriving of a single pair of supporting plates for all three components, and improved by the use of a single lever inside the supports, instead of the two outside (Fig. 8). Finally, the release was made self-setting by bending up the "handle" so that it was now pressed into position by the open breaker arm, as in Fig. 9. The chief advantages of this general pattern over its predecessors were certainty of action and compactness, the others requiring a special swelling in the containing case to accomodate them.

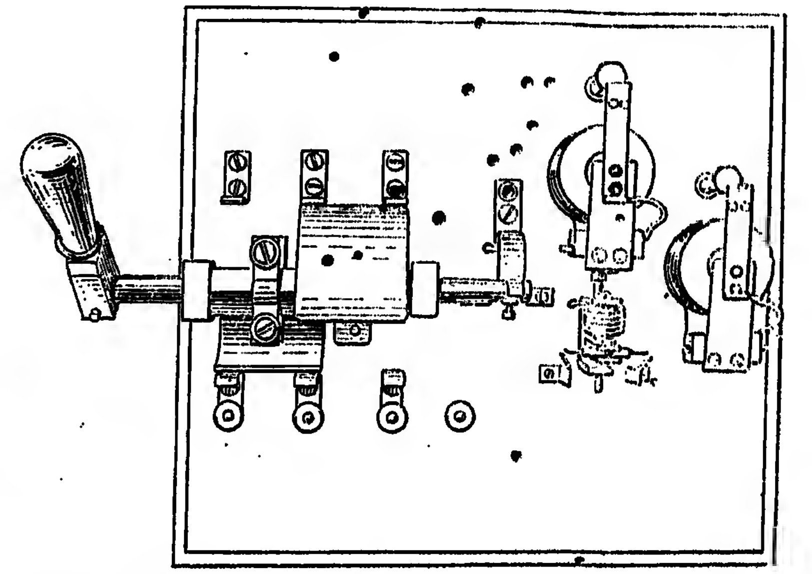

FIG. 14.—Second model of an automatic reversing starter.

The next three figures (Figs. 10, 11 and 12) illustrate the development of a beam relay for McColl balanced protection, as described in a recent paper before the

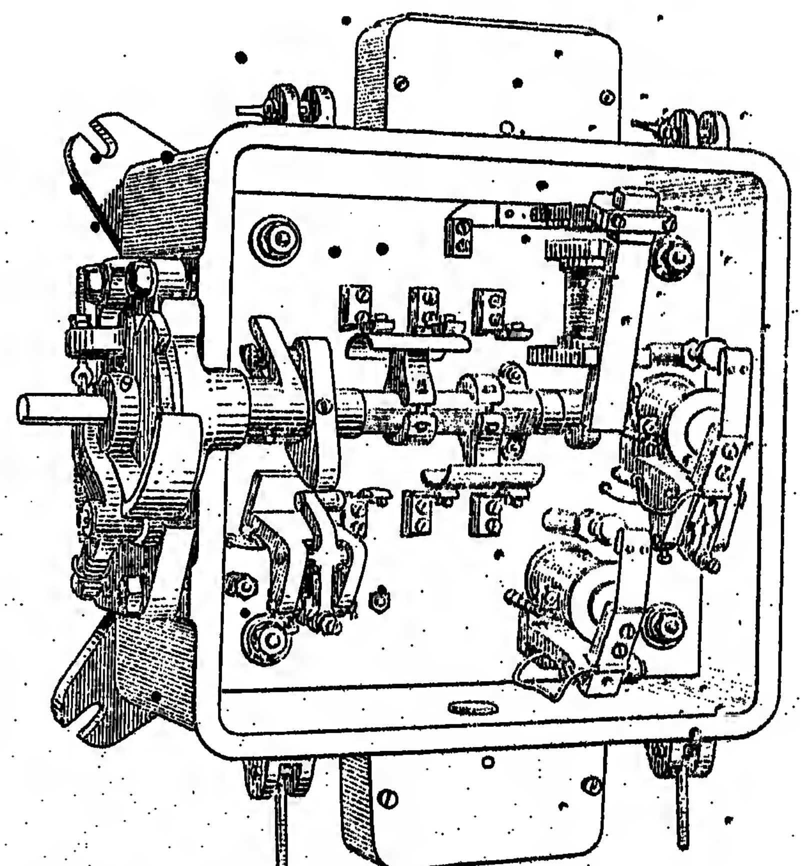

FIG. 15.—Final model of an automatic reversing starter.

Institution.* To begin with, a model was made up on a wooden framework, as shown in Fig. 10, in accordance with the details in the paper (e.g. Fig. 9, representing a parallel feeder protection scheme). After tests had

* A. E. McColl: "Automatic Protective Devices for Alternating-Current Systems," *Journal I.E.E.*, 1920, vol. 58, p. 525.

been made upon this, and the results had shown broadly the characteristics of the relay and the respects in which improvements were desirable, the model shown in Fig. 11 was constructed, having a nearly complete laminated iron circuit, and other improvements rendering it a more practical design. Exhaustive tests were now made until the relay was technically sound, whereupon the drawing office brought it to the form shown in Fig. 12, employing the necessary castings and moulded-insulation parts.

A final example, of a more elaborate collection of apparatus, is the reversing starter for machine tools, already mentioned on page 68 as having been evolved for controlling a radial driller. The analysis of the problem indicated that the connections from the line to the

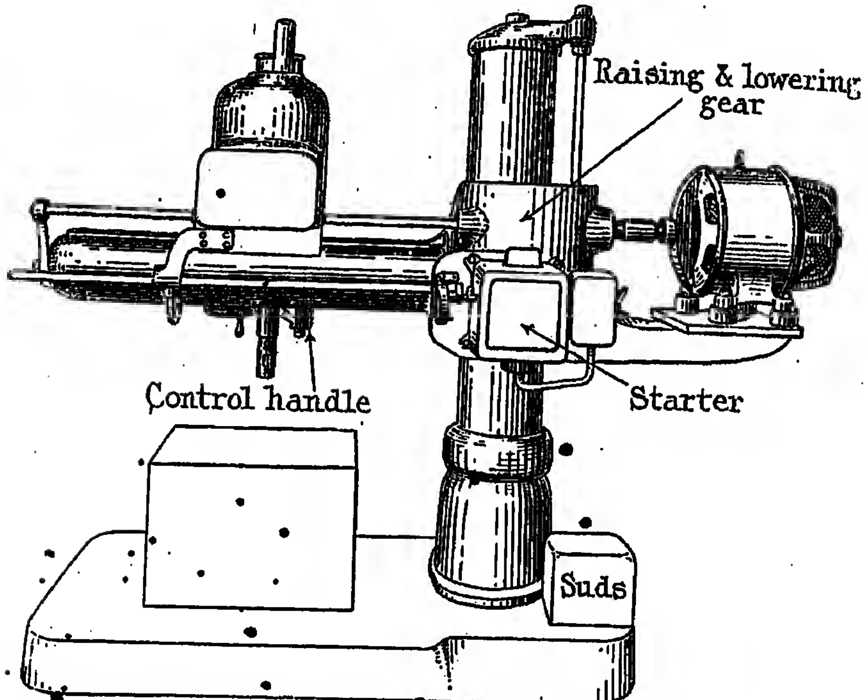

FIG. 16.—Final model of an electrically operated driller.

motor armature would be most appropriately dealt with by a direct reversing switch, and the acceleration by contactors and automatic relays interlocked with this. The first model, illustrated in Fig. 13, was accordingly made, in which a standard throw-over switch was roughly mounted in conjunction with simply constructed contactors and relays.

This was tested upon a motor, and its performance warranted the construction of a more practical model, shown in Fig. 14. The switch was now replaced by a reversing drum, especially designed for the apparatus, and the whole was brought approximately to the form and dimensions required in practice; but still the contactors and other parts were made up without the use of special castings. In this form the starter was mounted on an actual driller, and its operation was demonstrated to the machine-tool designers who had inspired the development.

This trial and inspection having been satisfactory, the final design was drawn out and manufactured, as in Fig. 15. In Fig. 16 it is shown in place on the actual driller for which it was developed.

The above are instances of a course of development continued until a saleable product has been evolved. The development does not, however, stop here; in fact, it can never be said to be complete, as tests and modifications still go on upon the latest pattern, resulting in continued improvement throughout the life of the apparatus.

The beginning of the whole process is the original idea, and a few additional words may be said as to how this is come by. The first essential is to concentrate upon the problem, until it has been thoroughly grasped in all its aspects by the imagination; and all possible assistance to the latter, such as the inspection of surrounding conditions, should be given. It is quite the usual experience for the actual solution to come after the matter has been temporarily laid aside; for example, when on the way home or during relaxation in the evening. Describing the problem to an associate is one of the best methods of stimulating the mind and inducing the desired response. Success is rendered almost impossible by mental fatigue, and this provides a further reason why the research worker should be safeguarded from unnecessary worry.

APPENDIX 3.

BIBLIOGRAPHY.

It is not proposed to add a complete bibliography upon the subject of research, since this has been excellently done by the English authors of two books that have appeared recently. These are:—

"Organization of Industrial Scientific Research," by Dr. C. E. K. Mees [McGraw-Hill], 170 pp., 7 ills., and "Research in Industry," by A. P. M. Fleming, C.B.E., M.Sc., M.I.E.E., and J. G. Pearce, B.Sc., A.M.I.E.E. [Pitman], 244 pp., 30 ills.

Both these works can be confidently recommended for their matter and their lucidity; and since they present the subject in American and English settings respectively, both text and bibliography are to a certain extent complementary.

The appended list of references (see pages 80, 81 and 82) relates to works that are likely to be already in the possession of, or accessible to, members of the Institution. They are indexed as for the first filing system, described in Section XI above.

Date	Vol.	Page	Matter or Title	Pages	Illus.	Author
			Journal of the Institution of Electrical Engineers.			
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April '15 ..	53	799	A Plea for Scientific and Technical Commissioners	3	0	Digby
Dec. '16 ..	55	37	R. and Future Sources of Energy	4	0	Robertson
Dec. '16 ..	55	48	Co-operation in R.	2	0	Stothert
Dec. '17 ..	56	4 & 6	R. and the I.E.E.	3	0	Wordingham
Dec. '17 ..	56	30	Scientific and Industrial R.	3	0	Fletcher
Dec. '17 ..	56	38	Linking up R. with Industry	4	0	Beaver
Dec. '18 ..	57	33	R. and Industry	2	0	Rogers
Feb. '19 ..	57	153	Planning a Works R. Organization	39	25	A. P. M. Fleming
Dec. '19 ..	58	2	Scientific R. and Education	1	0	R. T. Smith
Dec. '19 ..	58	26	Need for R. work	1	0	A. Ellis
Oct. '20 ..	57(s)	134	The Co-ordination of R. in Works and Laboratories	23	0	Constantine
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Jan. '23 ..	61	144	R. in Ireland	1	0	Handcock
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July '13 ..	pt. 3–4	869	A Few Notes on Engineering R. and its Co-ordination	25	4	Roberts
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15 July '09 ..	28	684	Industrial Fellowships	6	0	Duncan
31 Mar. '15 ..	34	255	Forest Products Laboratories of Canada	1	0	Bates
15 Jan. '16 ..	35	15	R. Men from the Manufacturers' View-point	2	0	Burgess
15 Jan. '16 ..	35	18	Administration of Industrial R. Laboratories	9	2	Bacon
31 Mar. '16 ..	35	338	Functions and Organization of a Technical Laboratory	3	0	Porritt
31 July '17 ..	36	814	Schemes for Co-operative Industrial R.	1	0	Rowell
31 July '17 ..	36	815	Some Principles of Industrial R. Organization	1	0	Rowell
15 April '18 ..	37	129R	Organization of Chemical R. in India	1	0	Holland
15 Feb. '19 ..	38	37R	Organization of a Factory Library	3	0	Barbour
			Proceedings of the Physical Society.			
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5 Nov. '09 ..	57	1010	The place of R. in Education	2	0	Sir H. A. Miers.
11 Feb. '16 ..	64	245	Organization of Scientific R.	19	0	J. A. Fleming
7 Dec. '17 ..	66	50	Discovery and Invention	12	0	Sir D. Clerk
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22 Nov. '18 ..	67	8	Possibilities of Scientific R.	12	0	Campbell Swinton
21 Feb. '19 ..	67	206	The Government, and Organization of Scientific R.	9	0	Sir F. Heath
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			Electrical Review.			
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Date	Vol.	Page	Matter or Title	Pages	Illus.	Author
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Discussion before The Institution, 1 November, 1923.

Mr. A. P. M. Fleming: The author has brought forward a most important subject at a very opportune moment, in view of the competition from overseas that electrical manufacturers are likely to have to face, and I am sure it is more than ever important for them to bring their products up to date and set their house in order. I wish to bring forward two very important reasons for having a development department or a research department, whichever it may be called. One is the need for consistent development, in place of the very spasmodic attempts at development often made in works. The other reason is the importance of removing from the factory every trace of experimental work. This is not by any means sufficiently realized by manufacturers even of the most modern school. I think that we all sometimes forget the very hampering effect that experimental work in the factory has, and one can fully sympathize with the author's complaints as to the tendency for foremen, toolmakers, draughtsmen and others, to experiment for themselves. The tendency is not at all confined to these particular kinds of employees; it is a natural tendency for engineers and others to carry out experimental work and thereby hamper manufacture. I think that no manufacturer will nowadays oppose the need for a development department, but I am not quite sure as to the functioning of the department as the author describes it. He indicates that the functions of such a department are to produce new designs as the result of representations from the sales, design, works or other departments, to study and observe electrical practice and then to remove technical burdens from the shoulders of the staff and works. Figs. 10 to 16 in Appendix 2 illustrate more clearly much of the work he has in hand, but I think it might be a little confusing and difficult if one were to try to apply this method of development organization to all kinds of electrical manufacture. I should be glad if the author would say whether in his opinion this department should actually function, as he describes it, with regard to all kinds of general electrical manufacture, or only for certain kinds of manufacture or certain sizes of works. In the electrical manufacture with which I have been associated both in this country and abroad, the functions which he describes would have to be dealt with by at least three, or possibly four, departments. For instance, the engineers would deal with calculations and the control of drawings for the manufacturing departments; the research department proper would deal with fundamental and applied research in connection with domestic problems as they arise in the works and the recording of data as the author describes, and the provision of new data for designs to assist the engineers in cases where they require those data. The development department would then consist of a department in which new designs are actually made up by hand or in which new tools, jigs, etc., would possibly be tried out and models or completed apparatus would be produced, fully tested and suitably processed and planned. In that sense a development department functions simply as a very great assistance in the economic development and manufacture of the apparatus, but it does not quite fulfil the function which the author has in mind in regard to relieving the engineers or in superseding the engineers' and draughtsmen's work. We may, of course, be looking at the matter from two quite different angles and have in mind two different kinds of apparatus, one of which might be suitable for the development department which he describes. I can quite understand, for instance, that it may be suitable in the case of switches and control gear, but less so in connection with other electrical apparatus. I am greatly interested in the author's remarks in regard to the staff. That is the most important feature of any organization, and perhaps particularly so in the case of research or development. An organization tends to centre itself round personality; if one has a strong and suitable man, the component parts of an organization will grow round that personality as a nucleus. As far as my experience goes, I have as a rule taken university-trained men and, whether they be physicists, metallurgists or engineers, have put them into the works for experience before they proceed to do research work. I think that such a plan is very desirable in a works organization, because the men get accustomed to the atmosphere of the works and its requirements, and learn the run of the works and so gain experience in dealing with the operatives. With regard to the question of suggestions, I had some experience a few years ago in setting up a system for obtaining suggestions from work-people. It was enthusiastically received at the beginning, but it did not work very well. I hope that the author's experience was more satisfactory than my own. The methods he suggests for recording data, and for organizing what is sometimes termed the "general intelligence system," are very interesting. It is very much a matter of opinion and experience how to deal with the vexed question of keeping up to date with the vast amount of scientific and technical data that becomes available. I have gained the impression that the author rather tends to depreciate the idea of foreign designs. I am not sure whether it is not quite a good plan to have a system of interchange with designs of foreign engineering concerns; it brings in a new view and, I think, can be utilized very satisfactorily. I should like to have the author's view as to the amount of money that should be spent on this kind of development and the complete functioning which he describes. As far as I have been able to ascertain from the figures of various companies, it would appear that a sum of from 3 to 5 per cent of the turnover should be allocated to what I should call complete development and research, or at any rate covering all the functions described by the author. If manufacturing firms would definitely set aside such a sum it would maintain a very regular and consistent, and much needed, attempt at development.

Mr. E. B. Wedmore: The whole trend of the paper is to support and advocate greater attention being given to the work of the development engineer, that is, to work directed to the conversion of ideas into commercial

models and products. In writing up development it is almost inevitable that there should appear to be some disparagement of the intellect required in other branches of the industry. In an engineering business it is, however, engineering which distinguishes the business from any other and which must be given first importance. One would look with suspicion at any engineering business which had no engineer upon its directorate, and which had not development engineers amongst the most highly paid members of its organization. Theirs is the work that puts profits into the shareholder's pockets, or, looked at from a higher standpoint, the service that the manufacturing concern is doing for the community is very largely measured by the work of the development engineer whose business it is to convert ideas into useful products, and this after all is surely the business of an engineering concern. I feel that the author lays insufficient emphasis on the engineering, as distinguished from the high scientific, side of the business. The boy who will be an engineer will, from his childhood upwards, show the engineer's gift of constructive ingenuity; and surely, if one has to choose, in adding to one's staff, between a man who has this gift and a man who has only a scientific qualification, no one would hesitate which of the two to select. It is a difficult gift to develop, but its development is all-important, and I agree with Mr. Fleming that every development engineer should be given the opportunity of becoming thoroughly familiar with the works point of view. The essential business of the work is to manufacture, and no one on the engineering staff can know too much about manufacture. One should place before the development engineer the detailed cost sheet of the piece of apparatus upon which he is to work. If he does any good at his work it will show in that cost sheet a year hence. The money value is not a bad measure of the value of his work to the community. By studying the cost sheet he can find directions in which there is room for real commercial improvement of the product with which he has to deal. The most vital part of development work is the experimental side. The development engineer whose services are not properly appreciated, when he asks for money for experimental work is regarded as being even less desirable than he was before, and yet the experimental side of the business is the vital part. Far too much material is made and sold in large quantities which has never been properly tested before it is put into production, and that is because the development engineer is not encouraged or given sufficient facility for making real tests; he has to guess far too much; he has to assume far too much for want of recognition by others of the importance of the experimental side of his work. The author goes on to speak of co-operation. Co-operation, in the sense in which he uses it, appears to be a co-operation of persons of diverse gifts who work together for the development of apparatus; it is what we call "team work." There is another aspect of co-operation which has been made possible by the work of engineers, and that is co-operation between competitors, which showed marked development during the war. Some of us have been trying to keep it alive ever since, and not without some success. There is no doubt that co-operation is one of the movements of the day which we shall see carried much further. We do not know what direction industrial reconstruction will take, but we shall see better co-operation as a feature. If any one country neglects this co-operation it will be left behind by the countries who develop it. Its advantages are obvious to anyone who will take a broad view of the situation; its difficulties are sufficiently obvious in particular cases. At the same time, if we can get particular men concerned in any manufacturing industry to meet round a common table, give them something innocuous to discuss, and then gently lead the conversation, we shall find that they have certain problems in common which they are all attacking, which they are all attacking inadequately, and which, if they can only be persuaded to join forces, they will be able to attack much more adequately with better facilities and to greater advantage. That has been the experience of the Electrical Research Association. It will be readily appreciated how directly most of the work of this Association bears on commercial development, and how much more it could have done if it had been started earlier. Consider the way in which various methods of laying cables have been developed without the help of the sort of experimental test which we have now carried out. After cables have been laid for many years and very heavy expenditure has been incurred, we find that some of the methods employed are wrong and should never have been used, notwithstanding that contractors and users had used such facilities as they had, and made such tests as they were able to make with their individual facilities. The same thing happened with regard to power companies and the development of poles for overhead lines. Now we get a sufficient number of persons together and make investigations and we find that poles for overhead lines ought to have been developed in a different way. Take switchgear for another example. I speak with feeling on the matter; one has had to make and sell, on a large scale, apparatus which one could not test because individual firms had not sufficient facilities. Recently the Electrical Research Association has spent a large sum in testing under working conditions, and I know that the author of the present paper will speak appreciatively of the sort of information which the individual manufacturer has been able to get from an adequate test carried out under proper conditions on a co-operative scale. Our work on insulation is also very largely development work, and it is safe to say that the larger part of the money of the Association is spent on development engineering. I hope the discussion to-night will be in the direction of commending that work, and indirectly the work of the Association, because the Association is the servant of the industry.

Mr. W. B. Woodhouse: The division of research into this so-called section of development is of great interest. There is a general feeling, I think, that all one wants for research is a laboratory and a staff of experts. I think the author rather indicates in the paper, but does not bring it out fully, that what is really wanted for research is an incentive, and that the real incentive in all this research work is reward. He speaks of the difficulty of getting co-operation. That difficulty is, I think, very largely due to a feeling on

the part of individuals, and perhaps of manufacturers, that they may not get their fair share of the reward, in money, in reputation, or in any other form that they expect it. If research is to be developed in this way and if manufacturers come together, no doubt a strong association of manufacturers is very beneficial because they can control the home market and they can be sure that each of them will get a share of the reward. If they have a good home market I suppose they can, to a certain extent, control the foreign market by dumping, but only to a limited extent; therefore they must progress and appreciate the essential necessity of working together. I think that the author has brought out this necessity very clearly in the paper. The expectation of reward may be a commercial incentive, but it is one which is necessary if co-operation is to be obtained. There is one other aspect that appeals to me, and that is that the electrical manufacturer has a class of customer who is, so to speak, an expert user of his products. The electricity supply industry uses the products of our electrical manufacturers and criticizes those products. The user is concerned to get a simple, cheap, reliable and efficient apparatus, and—perhaps because I am on the user's side—I believe that a great many developments are due to suggestions made by users who find out the troubles. Perhaps some of us on that side feel as a class that we do not get quite a fair share of the reward. Whether there should be a preference to the home user, or how the reward should be given, I cannot say, but we should like to feel that we were getting it. Ultimately, of course, we do get it in the improved product. I believe that the work of the Electrical Research Association of which Mr. Wedmore has spoken will help very much in that direction. There are many problems which we can all wholeheartedly tackle, feeling that the general reward is sufficient. There are some special problems, such as the development of particular pieces of apparatus, in which I believe the user might very advantageously be taken into consultation. During the past year or so I have been very pleased to find that our Electrical Manufacturers' Association has consulted with bodies representing the users as to specifications and forms of requirements, all of which tends to this proper sort of co-operation. I believe also that we ought, as far as possible, to take the universities into counsel. The teachers have a great deal to do to keep up with the times. Progress is very rapid; they have perhaps their own special research work and research interests and they are in some cases a little out of touch with manufacturing requirements or practice. If we could bring them in, I believe it would not only help the teachers in their own special researches, but also be most beneficial to the present generation of students.

Mr. C. C. Paterson: The author expresses his opinions very readily and fearlessly, and I am in cordial agreement with a great deal of what he says. I think he sums up the real object of the works development laboratory when he describes it as removing from the production shop everything which is not strictly productive work. I am afraid that the problem of establishing the principle which he lays down is one in human nature rather than in system, because one so often finds that the production manager whose energies could be usefully devoted exclusively to obtaining efficient production is very reluctant to devolve what he feels to be a large sphere of his work to an independent department which will be responsible for development. I think with Mr. Fleming that the author tries to prove a little too much in the paper. When he describes the development laboratory relating to a factory manufacturing electrical apparatus such as switchgear, electrical measuring instruments, telephone apparatus and the like, it seems to me that he is on very safe ground in the organization that he proposes, although one would like a little more information as to the manner in which he correlates the work of the development department with the usual works drawing office and production section. He gives an indication in the paper, but it seems to me that liaison must be a little difficult to arrange, and when he seeks to apply his scheme of works development laboratory to all sections of the industry—and, after all, the sections of the industry which do not manufacture appliances are very numerous indeed—it seems to me that he is stretching his case too far. I do not think that there is any universal rule which can be followed in deciding what is the right system and what is the right size and scope of a development laboratory; I think that every section of the industry and every section of manufacture must be considered on its own merits as to what is the best organization to apply. Let us consider the case of the thermionic valve. It appears to be just the sort of case in which one would require a development laboratory to work out designs and so forth, but actually in that particular branch of manufacture one finds that what the author would call the pure research man has to be responsible right through production and on to the finished product—to such a very great extent does a very slight deviation, quite unexpected and quite unknown to the production man, affect the quality and performance of the final product. Then on the other hand we have the kind of organization that the author describes, i.e. the second class, in which it may practically be said that, having worked out a model satisfactorily, the development department can release themselves from further responsibility. But there are many branches of the industry where works processes rather than models have to be investigated, and those may require a great deal of thorough-going research. There are other branches of work, such as chemical, metallurgical and mathematical investigations, at which the author hints. He suggests that these are functions of the development laboratory. I do not say they are not, but I think that the type of man who is suitable for the kind of work described in the paper is not usually the type of man who is best at that sort of investigation, and I do thoroughly disagree with the author as to the sequence of events in which he describes the genesis and application of any idea. We have heard a great deal about "pure" research. I should like to suggest what is the difference between research and development: Research is a search for knowledge and principles and laws, whereas development is the application of that knowledge. Now this search does not acquire any very special quality of purity, because the motive actuating

the worker is mere curiosity as distinguished from the motive of the worker who hopes that ultimately the knowledge he finds may prove to be of some benefit to the community. In our experience at Wembley some of the most ordinary works problems yield material for the most "pure" research. Industry will, I think, produce only very ordinary and mediocre results if it restricts itself to reliance upon the universities for the supply of its original ideas. For instance, we should never have had the gas-filled lamp or the dull-emitting valve—to take only one branch of industry—if we had relied entirely upon universities for our new knowledge. I feel that the pursuit of knowledge as an end in itself will have to form a very integral part of our industrial system. I should like to repeat that while I join issue with the author in such generalizations as this, I do congratulate him on having urged the importance of segregating this sort of organization and research work from the production work itself. If he would only discriminate a little more clearly between research and development, I feel that the paper would even gain in value. Every industrial research laboratory does a certain amount of development, and every development laboratory does a certain amount of research; we should not like to segregate all research in one department and all development in another, because the research worker with his knowledge and enthusiasm must father the application of his work if success is to be assured, and obtain from it the inspiration and ideas for further work. An organization of industrial research workers which spends all its time in development work and does not use part of its energies in seeking for knowledge of the principles and the real scientific basis of the industry with which it deals, is merely living on its capital. It will soon become sterile and unproductive. It is by a judicious mixture of the two that a healthy industrial research organization is maintained.

Mr. E. T. Williams: It is well known that during the late war many new problems had to be faced, and though they were thoroughly discussed by scientific men it was usual to resort to experiment and development in order to produce practical and reliable apparatus. As a result of this, research, experimental and development work assumed a new importance in the annals of this country, and though its extent has necessarily been reduced to meet the financial stringency of the times, it is now established that such work is essential to progress and efficiency. Scientific advancement generally makes this phase of progress of even greater importance than in pre-war days. In the laboratory connected with the Electrical Engineering Department of the Admiralty, research, experiment and development are treated as separate sections of one organization, and the plan works very successfully. It can be stated that the great value of such work is due to the fact that it enables the designer or inventor to see in a practical form what he has in mind, and present-day laboratories in which organized development and organized research are carried out constitute a scientific method of making advances, as against the more haphazard methods of other days. The paper refers to the question of individuality and co-operation. All who have been associated with this class of work realize how very important is the question of staff. The very individuality of the British people is at once a benefit and a disadvantage in this kind of work, which must necessarily in many cases be team work. What the head of such an organization should endeavour to do is to reap the benefits of this trait of individuality but secure at the same time the benefits of team work. This is largely a personal equation, and my experience has shown that if one will only take the trouble it is possible to obtain men who will work together without losing their individuality. To effect this it is essential to see that every man gets due credit for his work. If a man feels he is getting the credit of his work, whether it is team work or not, he has a new inspiration to go on, very often against great odds. In arranging the staff the aim should be to secure a balance, i.e. all the members should not be highly scientific, or alternatively, all practical men, but there should be reasonable proportion between the scientific men and the practical men and those who have organizing and administrative ability. It is, I think, important to keep work of this kind away from routine work, otherwise one is bound to suffer and this is usually the development side. On the other hand many valuable suggestions can be made by those employed on routine work. In this connection there is, in the Naval Service, an organized system of considering any suggestion which any workman may desire to make, however seemingly unimportant such a suggestion may be. Each suggestion is carefully considered on its merits and in many cases awards are made. This system has inspired workmen to take a greater interest in their work and develop improvements. In any experimental or development work it is a great advantage for some man, other than a designer, to be engaged upon it, as this brings a separate mind to bear on the same problem and enables valuable suggestions to be made. One of the most important functions of such work should be the reduction in the number of parts and ease of manufacture of any piece of apparatus. In conclusion, I consider that discussion between the designer, manufacturer and user should be encouraged in every possible way.

Mr. S. W. Melsom: The author states that the standard method of testing fuses is to connect them straight across the circuit, and then to close the switch. This may be quite a suitable test for the particular fuses which the author has in mind, but it can hardly be called a "standard" test. Very much more information is generally required, and in particular it is essential to know the current which may pass when the circuit is closed. The specification of the B.E.S.A. actually requires that the resistance of the circuit shall be so adjusted that the current may rise only to certain values. There are few matters which present so much difficulty as the definition of a reasonable test for a fuse. The type of organization laid down and the direction from which suggestions for improvement may come are apparently suitable to one particular case but are scarcely capable of general application. The exact type of organization depends so much on the individual worker, and suggestions for improvement should be entertained from whatever quarter they come. In practice it is found that the research worker is frequently

able to make suggestions for improvements, and in a number of cases it has been found beneficial to transfer the design section or parts of it to the research department—a very sound arrangement if the calibre of the research men is sufficiently high. The author is perhaps not altogether fair to scientific workers in his suggestions as to their qualifications and limitations. One feels that the general air of "nerves" and aloofness with which the scientific worker is held to be enveloped is frequently due simply to affectation often fostered by those with whom he has to deal. It is, of course, agreed that research work cannot be turned out on the lines of mass production, and also that some men possessing ability of the highest order are at the same time blessed with a somewhat peculiar temperament. For a works laboratory, however, if the work of the individual is to be fully effective, he must, as far as is possible, absorb the spirit of the works and, like everyone else in the organization, recognize that times of stress have to be met. A great deal might be said as to the author's suggested qualifications of research workers. Like others, he insists that a university degree is a *sine qua non*. What is actually required in a research laboratory is good men with a *flair* for research. The number of men really capable of doing good research work is very limited, and it is a curious fact that some of the most successful, aye really brilliant men, in works research laboratories to-day are without the paper qualifications without which the author appears to think they are incapable of doing such work. The author has omitted one section of staff which I should have thought to be indispensable—I refer to the skilled mechanic. One at times finds a mechanic who is almost if not quite a genius in the origination and development of new ideas. Such men are rare and require encouragement, but it is probable that they could form one of the most valuable sections of the staff of a development laboratory.

Mr. F. Creedy: The previous discussion appears to me to show clearly that if we are to avoid confusion we urgently require a definition of what is meant by "research" and what is meant by "research workers." I was surprised to hear Mr. Fleming tell us how he prefers to train research workers by a certain combination of theoretical and shop training. Surely if "research workers" are produced by such a training, then this is only a grandiloquent name for a superior type of test-room assistant. That it is possible by any course of training whatever to produce genuine research workers out of average human material and then set them to work at a bench to discover regularly for 8 hours a day, seems to me a grotesque conception and I do not suppose for a moment that Mr. Fleming believes it can be done. Hence I must suppose that by research he simply means such ordinary testing as it is not convenient to make in the commercial test-rooms. If so, I think this ought to be made plain. The author's is the first sound paper on the subject to be read before the Institution, because, unlike other writers, he realizes that research is not a business and cannot be reduced to routine and that novel and useful ideas cannot be produced to order. Not that the power of producing potentially novel and useful ideas is rare. It is, on the contrary, fairly common, as is evidenced by the fact that some 30 000 patents are applied for every year, two-thirds at least of which represent technically sound inventions. We all know brilliant inventors who are, three or four times every year, close on the track of some new invention, frequently quite sound. What is rare is the power of persevering in the development of a single idea, ignoring side issues and overcoming all the difficulties which stand in its way, until it becomes a practical success. I think that it would conduce to a great deal more clarity if we divided research into three grades. The first, which it would be better to call "precision testing," is apparently what Mr. Fleming has in mind, and simply consists in making tests to a higher degree of accuracy or of a more refined character than is possible in the production departments. It is confusing to call those who conduct such tests "research workers," useful and important though their work is. On the other hand, their work may be inspired and directed by a true research worker, who certainly cannot be trained in any such manner as Mr. Fleming suggests. A second grade of research appears to be what the author has in mind, namely, the production, modification and development of existing types of apparatus as described in the latter part of the paper, in order to enable them to fulfil a modified function or their original function in a more satisfactory way, and the actual working out of these modifications so as to ensure that the design shall give no trouble in operation. This may be called "development of known principles." The third grade would be the production of radically novel types of apparatus which shall solve some industrial problem in a new way. Examples of this type are: (*a*) The development of the phase advancer; (*b*) the development of means of varying the speed of induction motors by cascade commutator machines as associated with the names of (for instance) Scherbius, Kramer and others; (*c*) the development of the cascade motor and other variable-speed a.c. types; (*d*) the development of a.c. commutator machines for variable and constant speeds; (*e*) the development of the motor converter; and many other instances that will readily come to mind. This may be called "development of new principles." If these distinctions between different grades of research are borne in mind, I think it will be found that the apparently conflicting remarks of different speakers, both on the present and on previous papers, can be harmonized by bearing in mind that they are made in respect of different grades of research. I should now like to draw attention to a rather different aspect of the subject, which may perhaps throw some light on what has already been said in the discussion. The author assumes that there is in existence a development department continuously engaged in working out new apparatus. Two questions arise with respect to this: (1) Who decides what new apparatus has to be worked out? And (2) having developed the apparatus to a state of technical perfection, can we be quite certain that it will not prove a commercial disappointment? From the author's point of view both these questions are irrelevant, but the fact is that someone must decide these two matters if a development department is to yield the advantage which it should yield. In this

respect the position of a firm of consultants is rather different from that of the head of a development department who regards such matters as being outside his province, since such a firm must be able to offer their clients advice on the commercial aspect as well. I should like to ask the author how the first of these questions is dealt with in the organization with which he is familiar. One of the functions of his development department is to cure troubles arising during manufacture, on routine tests, or after installation, and so far his work is provided automatically by the production departments; but it is usually found that the decision as to what development shall be done must be referred to the business heads of the firm. Now I have not found that business men are unfavourable to research; on the contrary, I have found them most eager to benefit by it whenever possible. The real cause of their reluctance to spend large sums, and the reason why the development engineer is regarded in some organizations as undesirable, is not that the business heads are unwilling but that they are puzzled as to whether the development will really pay. It is almost impossible to say whether it will pay, but the man who is best able to give a valuable opinion on the subject is the development engineer himself, and if he shelves questions of that sort, in my opinion he shelves the biggest part of the problem and performs only half the function which he should perform if he is to deserve the confidence of those who have to find the money. I have for some years held the opinion that a development department should work in close touch with the commercial side. The development engineer should first of all be a close student of applications; he should be constantly viewing the operation of all sorts of plants, studying their defects and considering how these may be remedied. On the other hand, one must not be deceived by statements which users sometimes make without a due sense of responsibility. One often finds that a user states that some improved apparatus would be of such enormous benefit to him that he would give almost anything to get it, but when it is offered at a price ever so little above the stand rd price he will have nothing to do with it. Now comes the second question, which the author is wrong to neglect. Supposing a new development has taken place and is technically a perfect success, will it be a disappointment to the commercial man or not? Here we must distinguish between the different grades of research. Many people may suppose that all that is now necessary is to send to the selling agency a leaflet describing the new apparatus, and all will be well. This will often be true as regards the development in what I have called the "second" grade of research, but where a development is of rather involved character, in what I have called the third grade of research, our difficulties are only just beginning. We have it on no less authority than that of Mr. Henry Ford, that there is never any demand for a new thing, and the ordinary salesman, unless he has been specially instructed, cannot sell such apparatus. He does not possess the technical knowledge to enable him to explain its new features to the customer in a convincing manner. How is the development engineer to bring home to the user the pains he has taken to overcome the preliminary difficulties? This is a problem which cannot be shirked, and he is the only one who can solve it. Let us look at matters from the customer's standpoint. Here is a new apparatus which, it is alleged, produces some novel and marvellous result; it is not true that the user has any prejudice against it; in fact he is anxious to benefit by any advances in knowledge, though as a rule he does not expect it to cost him anything. The development engineer must be prepared to go in the minutest detail into the user's individual requirements, to understand his business sufficiently to appreciate what those requirements really are and to make it clear to him that he really does benefit. Pamphlets and other advertising literature go only a very small way in this direction; nothing but a personal discussion can carry the matter through; and this is a very heavy burden upon the development engineer during the first few years of the new apparatus. At the same time it is of the very greatest possible benefit to him. In my own experience I have frequently found that a really thorough discussion with users of the way in which the proposed new apparatus can be applied to their work, has entirely changed my ideas and shown the necessity for developments in design which, previous to taking into account the user's point of view, had not been at all apparent. The development engineer who cuts himself off from this source of inspiration makes, in my opinion, a very great mistake. After the first few years a good class of sales representative will relieve him. In certain other cases the business heads, in starting a new development, have not realized the sales difficulties and are consequently rather appalled when they are faced with the fact that while the standard apparatus sells over the counter, so to speak, because the user knows quite as much about its uses and capabilities as the manufacturer does, novel apparatus requires a long and patient explanation.

Mr. P. M. Baker (*communicated*): Present-day conditions in the industrial world call our attention in a very urgent manner to our own position in the world's markets. It must be remembered that we were the pioneers in the huge manufacturing development of last century, and that fact, together with our national resources in raw materials and the native ability of our people, gave us a pre-eminence which had been severely challenged by other nations; notably Germany and America, before 1914. The war has simply served to accentuate the struggle, and we have now to realize that not only must we so produce the goods which we export that they will sell in foreign countries in competition with the products of the other manufacturing nations, but that our very life depends upon our success in so doing. With our diminishing stores of raw materials there remain only two directions in which we can cheapen production for export, viz. (1) by improving the efficiency of our production processes and appliances, and (2) by increasing the skill of the personnel of our shops, so training the workman that he will acquire a higher and more useful type of skill and greater effective speed than ever before. The author, in discussing industrial research, is directing our attention to one of the main divisions of the former of these matters of which the national importance cannot be over-

estimated, and is thus rendering the Institution and industry at large a service. Turning to the paper, while agreeing with the author that the head of a research department should have had university training (otherwise why give anyone such training?), I think we must realize the importance of the "works experience" component of his qualifications. It is not impossible for the holder of a university degree to be a fool in some directions, but, if our university training means anything at all, the chances are that he will have acquired greater ability to think clearly and broadly than those of his colleagues who have only had the training of the shops. I am in favour of the second man in the organization being selected mainly for his outstanding knowledge of shop processes, as I think the combination of a Head having first-class "college" training and some shop experience, with a second who is intensely practical but has some theoretical knowledge, is an easier solution than that of finding the "superman" described in the schedule of qualifications. In somewhat parallel circumstances I have known the combination to work very satisfactorily. The author seems unfortunate in his choice of examples to illustrate the work undertaken by the research department. Those selected are scarcely such as call for the "high university" type of worker; some indeed could have been entrusted to any intelligent artisan. Again, the special apparatus referred to scarcely shows special ingenuity or novelty. To quote one example, the brake pulley described (see Figs. 2 and 3) has been extensively used. I myself used it in Bombay in a "Joule's equivalent" apparatus fixed on a 4-h.p. motor. It was designed and made by students from sketches supplied and was not considered novel, although we were rather pleased with ourselves at the convenience with which results could be obtained with a "Soames" or a modified "Prony" brake either for determinations of J or when, purely as an exercise, it was used in brake tests of motors. The strong point of the paper seems to me to be the careful organization of records which is demanded. This is a most important matter; records *must* be complete, showing failures as well as successes, and handy, and in this direction the paper, by detailing an organization, should be very useful. There are two aspects of the case for research organizations which do not, in my opinion, receive the attention which they deserve. (1) Our manufacturers —with some brilliant exceptions have, until recent years, starved research. They had no use for the highly technical man, if we may judge by the salary they were prepared to pay him, for accountants and secretarial men usually received much more than the engineers. (2) Modern research calls for much more expensive and elaborate apparatus than the individual worker can generally afford, so that organized research seems bound to replace individual invention to an increasing degree as time goes on.

Mr. P. Dunsheath (*communicated*): I feel that the author's conception of industrial research is altogether too narrow. The title of the paper certainly suggests that he is dealing with only one part of industrial research, but the impression one gets on reading the paper is that this part equals the whole. Possibly in the particular branch of electrical engineering represented by the author, development is the whole story, but this is not so in all branches. More usually, large calls are made on a research department in connection with factory difficulties, the control of materials and processes, and many other matters which do not come within the scope of the author's "development." Possibly the reason for the different outlook lies in the fact that the author is engaged in a branch of the industry where the product can be represented by models and where technical processes are of less importance than actual design. The question of the relationship between the research department and the factory organization is of vital importance. Wherever the two come into contact there must be fusion and not a fence, and in this connection I feel that the policy of the last few lines of the first paragraph on page 64 is rather too autocratic to be entirely successful in operation. The author says that the production staff should be instructed to communicate their proposals, and that any attempt at private enterprise should be strictly repressed. While I agree that experimental work should, as far as possible, be carried out away from routine production, I do not think that the author's method will be found very helpful. In hydrostatics a vacuum will often achieve a result where pressure fails. In dealings with men much the same principle applies, and my advice to industrial research men is to get the interest of the production staff. Remember that a man who is doing a job all day and every day probably knows a good deal more about the details than you do, and let him see that you appreciate this. Do as much to advance an idea put forward by the production staff as if it were an idea emanating from your own department, and you will soon find that under the "vacuum treatment" of personal interest the ideas will flow in without any repression. One might say that this treatment helps to weld the research department to the factory organization at all points and is, as a matter of fact, the only path to successful operation. On page 64 the author shows how epoch-making inventions do not come from the uninitiated. Few of us have the courage to say as much in the face of popular opinion, but how true it is! The invention of the buffer spring by the carpenter playing with a shaving is typical of what may happen in the pioneer days of an industry, but as the industry becomes organized great changes do not come about in this way: they have to be worked out. In the early days of a goldfield the digger unearths valuable nuggets alone; but thousands of pounds' worth of machinery is necessary and thousands of tons of rock must be treated to produce the same result as years go by. The author's condemnation of slackness in the recording of research results is very necessary. A certain type of research worker, otherwise quite well-balanced mentally, cannot be brought to see the necessity of placing his findings correctly on record. To me it seems purely a question of honesty that when a man has spent £50 or £100 of his employer's money on an investigation he should place on record everything found, even if he has only discovered that a certain thing will not work. It has been claimed, I know, that the value of a piece of research is sometimes inversely proportional to the length of the report, but, admitting this, the argument in favour of complete records still holds. The

author's suggestion for recording ideas on cards is very sound. In a busy research department new ideas are so prolific that it is quite impossible to follow up any but a small proportion. Unless recognition is given, however, the springs dry up, and a definite system by which the ideas are preserved is most desirable. I find that such a record kept personally by the head of the department is a good incentive to the staff. It also forms a gold mine for future digging. The correct selection of research workers is of vital importance. The author refers to collective thinking: this is absolutely imperative and the man who is secretive, withholds his co-operation from his colleagues and is for ever watching for an opportunity of thrusting himself forward, is better out of industrial research. The mental advantages accruing from membership of a well-developed and well-equipped research organization are, after all, considerable and demand in return full and hearty cooperation from every member of the staff. As to the type of mind desirable, the author makes some useful comments on pages 65 and 66, and it seems to me that the whole matter can be summed up by saying that a research worker should be highly skilled in the theory and practice of the weighing of evidence. In this respect the scientific investigator may learn a good deal from the lawyer, who first ascertains what facts are proved and then decides what can be deduced from these facts. As an example of what I mean, electrolysis does not occur where a lead cable is laid in a dry pipe, and if a report states that electrolysis was caused by water in the pipe it may be assumed that the writer has mixed his known facts with the inferences deducible therefrom. This is perhaps a rather bald example, but it illustrates a type of confused thinking which is by no means uncommon. In conclusion, then, I would suggest that the two most important factors in the success of industrial research are the mental training of the research worker and the extent to which fusion is successfully accomplished between the research department and the factory organization. These two ends can only be attained by selection of men with character, and if the personnel is chosen with these points in view nothing can limit the value to industry of industrial research.

Mr. J. G. Pearce (*communicated*): The author has performed a valuable service in drawing attention to development work and its relation to research and production. It is not clear from the paper whether the development he describes is a function of the engineering department, but development is undoubtedly an engineering function. Designing engineers, however, are frequently overloaded with current commercial work, and it may be an advantage to devote a small staff to co-ordinate and encourage desirable development in conjunction with specialist engineers. The paper takes a rather limited view of development work, being concerned with the evolution of new or fresh, but not necessarily novel, types of electrical apparatus of small size. The paper is concerned specifically with design, but the author does not even mention the development of new materials and the methods by which these materials may be produced and applied in the shops. The slides shown make it clear that the work done is principally experimental development, which has to be differentiated carefully from manufacturing development. A considerable amount of manufacturing development will be required after the model leaves the development department, whereby the design is prepared with due regard to the commercial materials, shop equipment and tools available. Development procedure also varies according to the motive with which it is undertaken, to reduce manufacturing costs, to meet the requirements of a client, to introduce a new line of manufacture or to meet competition. It also depends to some extent on the source of the original idea, i.e. whether it comes from inside or outside the works. Valuable as models may be in some cases, their use is subject to limitations; thus the performance and characteristics of a machine can only be satisfactorily obtained from a full-size sample. The author would add to the value of the paper if he would define the relationship, either as it exists or as he conceives it desirable, between his development department and the engineering, works and research departments, and indicate how much time is required, on an average taken over many varied developments, for a piece of experimental development, and how much for the subsequent manufacturing development. The references to indexes of literature and information are scarcely full enough to permit adequate criticism. The first system is suitable for a small office index, but there is considerable risk in leaving the work to an untrained junior. Working from annual volumes introduces a considerable time-lag. In the more ambitious Wembley scheme there is again the apparent lack of a skilled indexer or librarian to arrange the all-important key words in the titles, and to deal with the classification generally. It is also difficult to persuade specialists to maintain up-to-date indexes of their fields of inquiry. An active library or intelligence service would aim at keeping the specialist informed of matters likely to interest him, and so relieve him of the trouble of examining quantities of periodical literature, or of doing translations, abstracts, etc. Much work best done by a library staff is also involved in seeking information relating to new subjects for inquiry. The suggestion that the most effective method of co-ordinating research is the more complete dissemination of data for the benefit of research workers was advanced by me in a Faraday Society discussion in 1919, and is amplified in "Research in Industry" referred to in Appendix 3. The appreciative references to the value of co-operative research through research associations are thoroughly justified, and the electrical industry should note that it is concerned not only with its own peculiar materials but also with materials covered primarily by other associations, for example the Non-Ferrous Metals and Cast-Iron Research Associations. Considered broadly, the paper is a contribution to the problem of the effective utilization of new knowledge in industry. This transcends in difficulty the question of promoting research itself, and the paper should assist considerably the movement towards the "functionalization" of development work.

Mr. E. Kilburn Scott (*communicated*): I want to see a research institution where anyone can carry out technical research, have use of testing apparatus and instruments of precision and be in an "atmosphere"

conducive to creative engineering work. This can best be done in an organization on some such lines as Prof. Kennedy Duncan had "the vision to organize" at the Mellon Institute, Pittsburg. Fellowships at this Institute are for one or more years and cover the salary of the research worker and expenses of materials, but the use of building, light, power, standard apparatus and instruments, etc., is free. In the course of time much apparatus has been accumulated from hundreds of researches already carried out, so a newcomer is supplied with apparatus and instruments very quickly. Just as industrial operations require carefully planned buildings and special apparatus and tools, and the co-ordination of many factors, light, heat, power, voltage, kind of current, etc., so also does technical research require a suitable environment or atmosphere. The main idea underlying the Institute is service to the whole community, and therefore the results of all researches are published after a certain period of time. Also there are clauses in the Fellowship agreement to protect the research worker regarding rewards. As one who has lived overseas for some time, I am very glad that the author has drawn attention to the importance of this country initiating inventions and improvements because of the prestige it gives abroad. Our people overseas look to the homeland to keep in the van of engineering progress, as was the case in the last century.

[The author's reply to this discussion will be found on page 101.]

North-Eastern Centre, at Newcastle, 12 November, 1923.

Mr. B. H. Leeson: As an alternative to reading the paper, the author has given an interesting lecture describing the experimental stages in the manufacture of certain apparatus. The title of the paper, however, covers rather a larger scope than this and I think that the choice of the name "Development Department" to denote an industrial research organization is hardly a happy one. The word "development" in its usually accepted sense only implies one particular branch of such an organization's general work. Why does not the author adopt the broader title of "Technical and Research Department," to which he makes a reference towards the beginning of the paper? The principal function of such a department should be to act independently in a consultative capacity, upon technical matters, to every branch of the firm's activities and not merely to development work in the factory. This calls for the closest co-operative working with all the various departments concerned, not necessarily to relieve them of "all technical burdens" (which I think would be as impracticable as it would be undesirable), but to relieve them of the more difficult problems and to assist them in the lesser. As a guiding principle, the technical and research department should deal essentially with all problems involving "unseen" phenomena, leaving the purely visible and constructive problems for co-operative working with the design staff. The laws of dielectrics, the physical properties of materials, and the high-frequency resonance phenomena which occur upon a high-tension distribution system under an arcing fault or atmospheric conditions, may be mentioned as common examples of "unseen" problems. Fig. A shows diagrammatically the general principle of one piece of testing apparatus that we use in connection with these. With the bank of condensers charged up to 85 000 volts, a discharge current of the order of 8 400 amperes at a frequency of 100 000 is "spilt" upon the apparatus under test. This corresponds to a momentary maximum of over 700 000 kVA. To reproduce service conditions, a power transformer is employed to supply the necessary "follow-on" power current. The paper does not deal with the commercial side of the question. A customer can only consider the price of a commodity in relation to its sound construction and technical qualifications. The ability of the vendor's engineer, or agent, to effect a sale from this point of view, depends entirely upon his faith in the particular article. There is therefore need for an organization to provide him with expert knowledge of the principles involved, the tests which the apparatus has satisfactorily complied with, and the conditions under which it can be most efficiently employed from the customer's point of view. I should like to know whether the author employs such an organization for

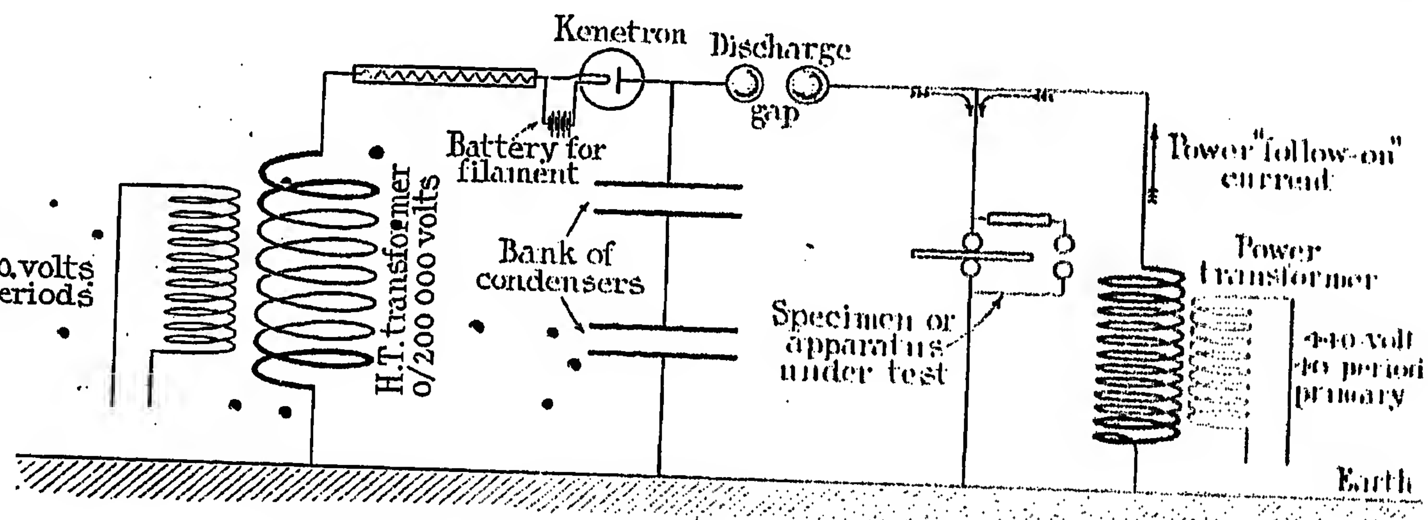

FIG. A.—Schematic diagram of connections for high-frequency surge tests.

the dissemination of the knowledge accumulated in his development department. The employment of a staff engaged upon technical and research work to embrace this purpose, in addition to the productive and other functions dealt with in the paper, becomes a sound commercial proposition and an actual necessity to any progressive firm. What, in the author's opinion, is the monetary limit (expressed, for example, as a percentage of the annual turnover) which may be economically expended upon purely research work? I think that every encouragement and the fullest consideration should be given to any suggestion, from whatever source it eminates. A suggestion on first acquaintance may appear small and possibly nebulous; its true value, however, should not be judged by this, but rather by its potential worth when transferred to the expert investigator. The manner in which a workshop suggestion is received and considered may prove, in many cases, as successful an encouragement for another to be forthcoming, as a monetary reward. As a technical and research staff consists, more or less, of a collection of experts, team work, for the good of the department as a whole, is essential. The qualifications of common sense, power of analysis, a keen sense of discernment and proportion, broadmindedness and the gift of application, are fundamental, and without these the possession of pure technical knowledge may lead to little practical attainment. I fully agree with the author's insistence upon every investigation and test being properly recorded and filed—a point which many investigators are apt to underrate. Regarding the question of national, collective, or individual research, I think that each one is equally essential in its own particular sphere, and that neither can dispose of the others. A closer liaison between these should be encouraged. No co-operative effort, however desirable on certain grounds, can dispense with a firm's individual need for an organization to deal exclusively with its own particular problems and developments. I witnessed the first official "flameproof" tests upon mining switchgear made at Sheffield University, and I can therefore endorse the author's appreciative remarks in regard to the work that has been carried out by that institution. I should also like to record my appreciation of the work carried out by Dr. Thornton, at Newcastle, upon the "Electrical Ignition of Gaseous Mixtures," as being another example of the assistance rendered by a university to industry. The switchboard described in Appendix 1 is very useful for repetition testing, but I should like to know how the author arranges his circuits and controls when making precision tests. Will he also state the degree of accuracy that can be obtained with the pressure indicator shown in Fig. 5? The last thing that I should expect this device to indicate would be the "crest pressure." I should be glad if the author would state why he employs an oil-testing apparatus which does not conform with the requirements specified and standardized by the B.E.S.A. The apparatus shown would give no reliable indication of the electric strength of the oil under test. With regard to the particular examples of research development work illustrated in the paper, I would suggest that in many instances certain stages in the development could have been either eliminated altogether or carried out by the design staff irrespective of the aid of any research organization.

Mr. E. Fawssett: I agree that it was an unfortunate national characteristic that we were prone to abandon enterprises just where they began to be profitable. Due to abnormal conditions this tendency disappeared in war time, but in some directions I have observed signs of its return. Co-operation between firms as well as between departments was largely assisted by war conditions, and while that incentive has passed and the national characteristic of individualism tends to reassert itself, the trend of development renders such co-operation increasingly necessary. That this is an accomplished fact may be judged from the number of co-operative research associations now at work. The current issue of the Privy Council Committee's report gives a list of 24 of these, nearly all of which have received substantial help from the Million Fund. As, however, this grant may be terminated after 5 years' work, manufacturers and users (especially the latter) will have to make greater efforts in the future if the industries are to benefit, as they should, from a properly ordered programme of research reasonably unfettered by financial considerations. The author sets out a training scheme for research workers which is probably ideal in theory, but unfortunately men trained on these lines are often unpractical and erratic. I agree that this is the fault of human nature rather than the type of training, but I consider that research workers for the higher positions (as distinct from mere intelligent observers) are born and not by any means made. I should say that the equipment of a research organizer would be a large portion of that rare gift "common sense," another of "tact" to deal with a diverse and probably unusually temperamentally "difficult" staff, and an excellent knowledge of first principles. I think that the training suggested by the author is hardly "human" enough, and in this connection I would mention that one of the questions asked of young engineers seeking positions on a large concern with which I am acquainted is: "What success had you at games at school?" The training and experience so gained is most valuable in "team work," and in acquiring that outstanding British characteristic of "playing the game."

Mr. H. Parry: My experience of research is more from the user's point of view, so I propose to confine my remarks rather to detail than to general organization. I agree with the author that buildings should be as free as possible from vibration; much time can be lost due to this trouble, particularly if one is doing ballistic measurements or using reflecting instruments. Books of foolscap size are, in my opinion, much better than the loose-leaf system; there is always the possibility of a leaf being lost in the latter system. Referring to the author's abstract cards; if abstracts are too condensed the information is sometimes misleading. I should like to make a plea for greater support for *Science Abstracts*, which forms a very complete abstract of the current published science and engineering data of the world. It seems to me that instruments on the author's switchboard may be affected by heat

from his rheostats, and magnetic fields from his heavy-current circuits. I have found iron-cased instruments to be in error to 1 per cent or more due to a lead about 1 ft. away carrying a current of 700 amperes. I think that an oscillograph or an instrument of that type is preferable to the one described by the author for studying switch motions. In general, these motions or their rate of change can be transformed into electromagnetic effects to work an oscillograph.

Mr. T. Carter: While we must all agree that the author advocates a useful, indeed a necessary, adjunct to the activities of manufacturing firms, I think it must also be agreed that the setting up and the maintenance of a research department presents varying difficulties in varying types of firms. In a very small firm, for example, the head of the firm, personally active in directing it, will probably usually have to be himself the research department, which is a satisfactory solution of the problem, or the opposite, according to the temperament of the man; in a larger firm, but one still comparatively small, there must be a separate staff for research, and the cost of such a staff may conceivably be a serious item in the bill of expenses, making the firm hesitate before taking any elaborate steps in this direction, and perhaps compelling the combination of the research department with some other department, which is not always a satisfactory solution. Generally, the larger the firm the less will the expense of research be felt, which leads to the conclusion that research establishments common to a whole industry, or at least to a section of the industry, and supported in common by the members of that section or of the industry, are most likely to be fully useful. I am inclined to think that "investigation" would be a better word than "research" to describe the process dealt with in the paper. The pursuit of knowledge by pure scientific research has in view merely the discovery of something for the sake of discovering it, its nature being often altogether unspecified and utterly unknown; but industrial research, so-called, does not appear to be a lurking-place for surprises calling for review and revision of fundamental things such as may be encountered with exciting frequency by anyone undertaking the more ideal kind of research. Someone, in fact, recently described it as a rather belated realization of the truth that business is business; and it was only ten days ago that I heard several examples of the calamitous effects of neglecting to investigate before new things are made. It is a fresh testimony to the wisdom of the counsel: "Look before you leap." Industrial research on the lines described in the paper is the systematization of what goes on in every factory that is not a mere machine for belching forth undigested articles on the turning of a handle; and the value of the systematization is that, under it, ideas once conceived are less apt to be strangled at birth than they are when there is no one to nurse them skilfully. The scheme is for the ordered materialization of an idea by means of an investigation starting from a known point to reach an end that will fulfil a predetermined purpose. I value the reminder that ideas may come anywhere but in the ordinarily expected and set-apart places; for myself, I find a crowded street sometimes as useful a place as any in which to let my thoughts take shape. The author is right when he indicates that though we as a nation produce great initiators—great men, that is, with the power of revealing great things that have been hidden until their time—we are often weak in applying their new ideas to practical ends, particularly when the stimulus of the immediate presence of the initiator is withdrawn; and sometimes we have even failed to realize the greatness of the new work and have allowed the man of vision to starve. We have been called a nation of shopkeepers: is it that we are so busy with our buying and our selling that we will not risk a little of the present to win a finer future, not to say a more lucrative one? It is often said that a certain political creed, if put into practice, would stifle initiative; but it could not do that, for what is in a man like Newton will come out of him somehow in any sort of circumstances. What is thought of as likely to be stifled is really the imagined desire of the ordinary man to leave things a little better than he found them; I sometimes think that the alleged fear is expressed only to keep us a little longer from realizing that the great majority of people have no such desire, and that it could not exist in the dreaded circumstances because it does not exist now. Our nation does not usually look at things from the same point of view as that in the paper; perhaps it ought to do so, and perhaps persistence in the end will teach it; but let us realize the problem to be faced and the battle to be fought. There are too many instances in commerce and trade and industry of deliberate refusals to do insistently needed things; there is too much of the tendency, inborn and inherent, to travel in the old rut, even when the better way is pointed out. "Compromise"—"Good enough"—"No harm in it"—these are common but fatal watchwords against opposing nations with characteristics that naturally make them pick up ideas anywhere, internally, externally, on the right hand and on the left, and build up something out of them. I refer members to an example of this sort of thing that was mentioned in the technical Press only a week or two ago. Inertia, the refusal to change the ancient way, is a horrid sin when it grows into a habit. We are individualistic; we do not readily co-operate; sometimes, even yet, things are kept secret and apart when they ought to be widely known—things that would add to the national efficiency and prosperity and so in the surest way to the prosperity of every concern and finally of every individual in the country. Unless we prosper in every unit, any show of prosperity is a hollow thing. All this is proper comment on the paper, which is a plea for the sort of work that will bring us more closely together for our mutual good. Those of us who have already been trying to go in the way it points out will be stimulated to greater efforts by it; and no one can read this record of actual achievement without feeling that it is worth while to go on, and that not only in manufacturing, but in every branch of the industry, the ideals that underlie the proposals of the paper are somehow capable of being realized.

[The author's reply to this discussion will be found on page 101.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 14 NOVEMBER, 1923.

Mr. F. R. Combes: It would seem that greater co-operation in research work is most urgently needed in this country. This applies particularly to the period following the "philosophic" research stage. With greater co-operation between the universities and industrial concerns, for instance, each would attend to the work best suited to its resources, the universities undertaking work requiring the expenditure of much time, by thoroughly qualified men, while the manufacturing concerns would carry out research requiring the use of large quantities of power and apparatus. The final development can only be carried out efficiently by the manufacturers themselves, through the medium of suitably trained men with the necessary practical experience. The necessity of taking full notes of all relevant matter during the test has been mentioned and cannot be too highly emphasized. During a test the operator is steeped in his subject, but on changing over to a fresh piece of work the mental notes of the last test vanish with remarkable rapidity. The author stresses the necessity of highly trained men, and it is interesting to note that practically every important discovery has been made by a man who has devoted his life to the work. The half-watt lamp was made possible by the discoveries of Raleigh and Ramsay. The telegraph was the result of a series of discoveries starting with that of Oersted; this was carried on by Ampère, and his results were investigated and continued by Gauss, Weber and Henry, and their researches resulted in the first workable telegraph. All these men were highly trained investigators, and these examples might be continued indefinitely. To extend the author's analogy of the gold-seekers; it is technical training that enables an investigator to distinguish between pyrites, or as it is more commonly called on the goldfields "new-chum gold," and the desired mineral.

Professor W. Cramp: The paper arrives at an opportune moment, for the advent of the Research Associations and research departments in works renders it necessary that a discussion should take place upon the functions of these establishments as compared with the research departments at universities and technical schools. It seemed at first as though, between philosophic research in the physics departments of the universities and these new works developments, all research in the applied science schools would be squeezed out, but it is perfectly clear from the paper that the work undertaken by a development department is of an entirely different character from that which we do at the University. In this connection, one cannot overrate the importance of "atmosphere." In a works the conditions are always certain to be subject to limitations of time, and the atmosphere is unsuited to the conditions of concentration and leisure that are required for inquiries into fundamental matters. Thus in the universities that research which has taken the form of the complete development of a new apparatus will gradually disappear, as will also those tests of completed machines which are much better carried out in the works. The function of the applied science research department, therefore, will be to take hold of the basic principles as the physicist leaves them and show how such principles can be usefully applied; and to reduce the laws governing them to a form that can be utilized by a development department. To take a concrete instance, the principles underlying Kapp's phase advancer would be worked out in the university, but the actual form would be developed in the works. Or, again, and as a converse case, such a research as that carried out by the author in connection with liquid rheostats would have been much better performed in a university, since he was obliged, from limitations of time and opportunity, to omit important considerations and to announce general results which are only roughly true. It is obvious that co-ordination between the works and the universities is much to be desired. Another function of university research departments, and perhaps their most important business, is the training of men to be capable of undertaking works' research and development on thoroughly reliable and scientific lines. Each year I am more and more impressed with this necessity and with the immense amount of training required, and I do not think that the summary on page 66 is by any means adequate for this purpose. I find that, although ours is a four-year degree course, research men in their fifth year still need advanced lectures and training in the application of mathematical functions, as well as development of the attitude of mind to be adopted in regard to any research problem towards which their attention may be directed. In this connection it is much to be regretted that when such men have been trained there is no works in this country which has an adequate organization for giving them the practical specialized training by means of which they may be made fully efficient in a development department. I think it is high time that works' directors should consider this problem. In conclusion, I should like to thank the author for outlining the methods of filing information, which have been a source of trouble to so many heads of technical departments.

Dr. M. Kahn: Industrial research has in recent years reached a new stage as the result of the progressive specialization and the tendency to subdivide work, namely, that special departments, concentrating entirely on this work, have been created in many manufacturing concerns. Such an arrangement improves the efficiency of a manufacturing organization, as it frees the bulk of the staff and works to concentrate entirely on production, the development department dealing with new designs, improvement of existing types, troubles in manufacture, testing of new materials and new processes and other matters, which are outside the scope of the daily routine work of manufacturing. Such an arrangement presupposes a subdivision of work such as is usually only found in large organizations, and this fact should not be forgotten, as an explanation why such organizations have been more numerous in other countries, especially in the United States. Whilst this subdivision allows a greater amount of specialization and concentration in the purely manufacturing side of the works,

which is in itself desirable, it introduces on the other side a number of workers, who can take a broader view of the questions that arise, thus counterbalancing the narrowing of outlook which specialization often brings about. This consideration shows how important it is to choose for the development department men with a training on a comprehensive basis who can look on a subject from several points of view. Such men should be, if at all possible, those having experience outside the particular scope of the work. Such men can introduce new ideas and keep in touch with developments in other factories and other trades. In this way the advantages of specialization can be combined with those of versatility.

Mr. W. F. Higgs: The author refers to the fact that we have grown accustomed to abandoning our enterprises just where they begin to be profitable. Unfortunately, this is a failing of an engineer. He naturally has an inventive mind, and one must not expect him to convert himself from an inventive to a productive being. The author uses the term "mass production." I cannot remember the use of this before the war; it implies to the uninitiated new methods, and to most people methods evolved during the war. Without reviewing the whole history of production, what better example is there of "mass production" than the printing press invented six centuries ago? The author implies that there is not so much scope for industrial research and repetition work as in other classes. I disagree with him; finality is never reached, as the more one knows of repetition work the more scope there is for industrial research. He refers to limit-gauging, but in my opinion gauging is useless without applying limits. When we refer to a dimension, limits are implied, but that is not sufficient; they should always be stated. The author refers to the university degree in engineering. It is very important that young men about to enter the profession should take this degree. The great advantage of university training is that it teaches people how to learn. The author points out the importance, when investigating a proposition, of finding what has already been done in that direction before commencing work, and his method of indexing is of great assistance in that direction. He says that the private worker is at a greater disadvantage to-day than formerly, but I doubt if this statement is correct. He implies that the particular testing apparatus necessary is not at the worker's disposal, but he must remember that formerly this apparatus was not in existence. I am of opinion that a modified form of such a paper as the present should be brought to the notice of financiers. Research costs money, and before it can be done money must be found. On what does the success of a nation depend? A banker will say finance; a merchant will say foreign trade; politicians, at the present moment, the tariff question. I say it is combination, and the smallest component is not industrial research. Our success during the last century is to a large extent the result of industrial research carried out by Watt and others.

Mr. W. Lawson: The author's contribution to the subject of industrial research is of great value as it is based on a bold and apparently successful attempt to put the idea into actual practice. Notwithstanding all that has been said, and the evidence of research activities given in the paper, one has serious doubts as to whether the average British manufacturer is yet wholly convinced of the necessity of adopting such measures as are advocated by the author. There is indeed absent from many standard lines of electrical products that appearance of finality in design and construction which can only be achieved by those possessed of the requisite equipment, knowledge and technical skill. Moreover, instances are not lacking of misdirected development whereby successful designs have been altered to their detriment for the purpose of cutting down weight of material and cheapening the method of manufacture. What usually results in these cases is a diminished reliability in service which in consequence increases the cost of maintenance. The attitude of the British manufacturer towards technical research, and his reluctance to pursue his enterprises to ultimate completion, are not explainable by national decay, conservative outlook or temperamental inability to co-operate. Possibly the explanation is to be found in the peculiar trade conditions existing in this country, but this leads to considerations which are outside the scope of the paper. It may, however, be confidently expected that with the spread of the spirit of research this problem will in due time be susceptible of solution. I agree with the author as to the impossibility of epoch-making discoveries coming from untutored sources, but would go further and add that it is improbable that any such discoveries will have their origin in the development departments of industrial concerns. The author attaches insufficient value to suggestions and ideas from outside sources. It should be remembered that many of the articles in common use have been brought to perfection through suggestions from users, and one of the signs of the times is that the general public are rapidly acquiring what I might term the "electrical sense." The growing use of electrical appliances is bound ultimately to open up sources from which valuable suggestions for improvements may be looked for. In this connection, and also in its attitude to those employed in a works who are not specifically engaged in development work, the author's outlook is perhaps too exclusive.

Dr. C. C. Garrard: I think that the author's remarks on page 64 relating to "private enterprise" might be misunderstood. It is very important not to suppress initiative anywhere within an organization; many valuable suggestions emanate from the workshops, for example, and it is desirable that these should not be discouraged. It is important to distinguish between industrial research and industrial development. Take, for example, oil switches. An industrial research might concern itself with the phenomena associated with breaking electric circuits under oil. The development department, however, deals with the production of an actual piece of apparatus which can be illustrated and priced in a catalogue. This kind of work is especially necessary in connection with switchgear and the like, the designs of which are not amenable to pre-calculation as are, for example, those of electrical machinery. This work, however, entails just as high a class of man to carry it out as does research work. The function of the drawing office is

to produce designs which are mechanically feasible and capable of being made in the works. The drawing office must also embody the tradition of the organization and be the repository of experience gained in all parts of the works. When it comes, however, to breaking new ground and developing a new piece of apparatus, generally speaking, something more is required than is available in the drawing office staff, and it is here that the development department comes in. Of course, there are many draughtsmen who are original and quite capable of making developments. If they show themselves to possess this capacity then they should certainly not be repressed but should be allowed free play. Hence, I do not think that such a hard-and-fast line as is set out in the paper can be drawn. Originality, inventiveness and initative are the things that keep a works going; they must be welcomed and encouraged wherever they occur. By this I do not mean that the functions of the development department as outlined by the author are superfluous. On the contrary, it is because in the ordinary working of a factory we do not have sufficient of the qualities just mentioned, that a development department is necessary and is organized primarily as a vanguard of the forward progress of the works. It is the business of a development department to develop new ideas, to make new designs, and to produce data upon which new designs can be based. There is no doubt that development departments have come to stay. For their efficient management and operation they need men of considerable intellectual and educational attainments, and they should receive as high acknowledgment from industry as does, for example, the commercial department. Progress and evolution in engineering affairs have to be organized, and a necessity to this organization is a development department. Money spent there is in the long run the best investment, as, without this department, stagnation and retrogression speedily assert themselves.

[The author's reply to this discussion will be found on page 101.]

Discussion before the Mersey and North Wales (Liverpool) Centre, at Liverpool, 19 November, 1923.

Professor E. W. Marchant: The subject of industrial research is one that it is very fitting should be discussed by the Institution, because the Institution has had no small share in promoting such research during the past 10 years. The Research Committee of the Institution was founded many years ago, and out of that arose the Electrical Research Association, which later became connected with the Department of Scientific and Industrial Research. The part of the paper which interests me most is that dealing with co-operation between the industry and the universities in research work. In connection with any scheme of research the chief function of a university is the training of research workers, which has been referred to in the paper. The author points out on page 66 that it is necessary for research workers to be trained in the art of clear and logical thinking, then in research by a study of physics and chemistry and, if possible, of geology, and lastly, in the art of expression and languages. The latter is, I think, very desirable, but at the same time one is bound to point out that it is a quality very often not possessed by some of the most brilliant research workers. It is unfortunate, because the fact that a man is not a good expositor tends to depreciate the value of his work to the outside world. It is very often difficult for a research worker to express himself clearly, and it is very difficult indeed to train him to do so. At the same time, clear expression is a very important matter, and he should certainly be trained in the art as far as possible. Again, the author refers to the necessity for training in the practical applications of science. I entirely agree with that, and I think that research workers undergoing training should be encouraged to make things for themselves. It was my good fortune to be associated with the late Mr. Duddell in some of his early work, and I think his extraordinary success was largely due to his mechanical skill. We always lay great stress on that in the training of research workers in the University of Liverpool, and there is no doubt that it is of great assistance to them afterwards. In the second part of the scheme of training I should also like to suggest that more stress should be laid on the study of applied science. The author does not, I think, attach sufficient importance to the necessity for studying applied electricity. I am very strongly of the opinion that the advantage that is to be gained by a research worker by spending a considerable amount of his time in studying the appliances which make use of electricity, is very great. Scientific training can be given quite as effectively by a detailed study of an electrical machine as by the study of an experiment in pure physics. "Massed research" is a method which has been largely used in America and which developed rapidly in this country during the war. By having a group of men engaged on a problem, much more rapid progress is often made than by the same number of men working independently on the same problem. This method of attack is bound to develop as industrial research progresses.

Mr. J. G. Pearce: I would suggest that development work should be regarded as a "load equalizer" for the engineering staff during slump periods, as then the time and equipment are available. During prosperous periods when money is available for development work it does not get proper attention. This involves a regular and continuous development policy. I should be glad if the author would deal with the following questions in his reply: (1) What relationship exists in his works, and generally what relationship does he consider desirable between the engineering, manufacturing, research and development departments? (2) Where a progressive firm pursues a continuous development policy, what annual sum expressed as a percentage on profit and loss or turnover should be set aside for research, experimental development and

manufacturing development? (3) What average time does the author find is required for experimental development of the kind he describes and for the subsequent manufacturing development? And (4) what method or system can he recommend in a works for determining development policy, bearing in mind that suggestions for development come from outside inventors, from engineers and salesmen in the company, or from clients?

Mr. J. H. Collie: While I agree that a research department is a very necessary adjunct to manufacturing firms, it appears to me that only the larger firms can afford to run a department of this kind. I think it would be a good scheme if there were some public research department which would for a fee carry out tests on apparatus manufactured by smaller firms, and which would issue a certificate that such apparatus had been duly tested and found satisfactory. Such a certificate would assist users in getting reliable apparatus, and afford some guarantee that it would function satisfactorily under all conditions. This might remove some of the shoddy apparatus at present on the market.

Mr. B. L. Myer: Mr. Pearce has raised the question as to who and what should determine the particular line of development or research to be undertaken, and I suggest that usually under commercial conditions the economic factor determines it. In other words, will the result be a profitable one? The person or persons generally responsible for determining whether new developments should be embarked upon must of necessity take this responsibility. I think the economic factor is one which the author should examine closely in connection with this matter. The point raised by Mr. Collie is also of interest from an economic standpoint, because it appears to me that such research laboratories as have been indicated in the lantern slides are only within the reach of such concerns as have vast resources of capital. Perhaps it would be useful if the universities were in some way provided by means of Government funds to enable them to act for the smaller firms, who could submit their problems to the specially skilled people in the university, to be dealt with on their behalf.

Mr. O. C. Waygood: The chief work of any research organization should be to search for knowledge or information concerning manufacturing processes, the selection of materials and the utilization of waste by-products, leaving the actual development to the engineering staff, who by their training and experience are best able to deal with such problems. What in the author's opinion would be the chief work of the development department? Does he mean that an employee anxious to put some new scheme forward should pass it on to the research department for them to develop? Surely, the right place for this idea to germinate is in the mind of the originator. On the other hand, would employees be willing to divulge their secrets if such a system prevailed, especially if they knew that it was not for them to carry on with the idea? Does the author suggest that this department should take charge of every possible branch of the products of an industrial organization? Apart from the impossibility of organizing such a department, the only place for the development of any new idea is in the environment of the department set aside for that particular product. The author on page 64 points out that draughtsmen and foremen are exposed to a natural temptation to experiment for themselves. There is no reason why this should not be encouraged, provided it is confined to senior and trustworthy employees, and to hinder or prevent it in any way would be fatal. New developments are not being evolved every day and so would not unduly disorganize the work of the department. On page 69 the author suggests that a firm desirous of making contactor gear, for example, and not having previously done so, should put this in charge of some suitable member of the staff. A close study of the advertisement columns of the technical Press suggests otherwise. On page 73, under "Co-ordination" the author criticizes a scheme proposed some years ago whereby every research worker whether in a university or works laboratory would work under a staff appointed by the Government. He condemns this scheme and suggests that it would stifle research. I quite agree with him, but if he does not like this particular Government scheme, why suggest its application in a smaller degree in industry? It is for the industrial concerns to encourage their employees in development and suggest, in the interest of each, ideas which will eventually benefit the whole and so keep electrical engineering development in the forefront. Adam Smith in "The Wealth of Nations," remarks: "The wages of labour are the encouragement of industry, which, like every other human quality, improves in proportion to the encouragement it receives."

Mr. W. Holttum: The author states in Section IV, in reference to the causes of the present position, that much of the pioneer work of British scientists is built upon by foreign nations rather than by our own, and points out that while individual work succeeds up to a point, beyond that point co-operation and co-ordination of the results of different workers are a necessity for progress. In Section XIII he comments rather cautiously on the means of co-ordination made possible by societies, the Electrical Research Association, publications, etc. Nevertheless, the fact may as well be recognized that a large proportion of the useful research work done is carefully guarded from publicity for competitive reasons, and there must, therefore, be a great deal of overlapping of endeavour and inefficiency of utilization of the sum total of the results obtained. It is hard to see how this state of affairs is to be rectified, since the needs of individual firms can in many cases be best met by their own individual research work, and they are naturally loath to give away the results of their experience. It seems evident, however, that a system of free interchange of knowledge would benefit industry in every way, and it is probably a fallacy to think that undue prosperity would attend the business of the selfish manufacturer who tried to profit by utilizing the brains of others. If it were not that a great deal of the information which is attempted to be hidden leaks out or is unavoidably given away by the manufactured product, progress

would be far behind its present position. I think that a system of free interchange of information might be initiated by the more reputable manufacturers in each line of business, and it would be a step fraught with great possibilities.

Mr. J. A. Morton: The author mentions that progressive standardization has opened the way for quantity production: he might also have added, "and development." This is well illustrated by the British Standard Specifications. The formulation of these Specifications gave manufacturers more time to devote to other problems. For instance, before electric light cables were standardized, different makers employed different thicknesses of insulation, lead, etc., consulting engineers had their own pet specifications and consumers their particular fancies. The Cable Makers' Association took this question in hand and standardized the most common cables, which was a great gain to everyone concerned. Later on, the British Standard Specifications were produced, and these provide a solid basis for further development. It is not clear to me how the head of a development department (though he must obviously be some sort of superman to perform all the duties which the author lays on his shoulders) can himself deal with all sorts of suggestions made from the selling side of a big business, from consumers and from workpeople. He needs to be a man of university status, as the author says—meaning, I suppose, exceptionally well educated and not that a university education is a *sine qua non*. There are many men who have done good research work without a university education, although there is no doubt that the grounding in first principles which such an education gives is very useful; still, this does not necessarily give a man an adventurous and initiative mind such as would be required for the head of a development department. Professor Marchant has referred to the question of the necessity, or otherwise, of the research engineer knowing several languages. My own feeling is that the most important thing in these days is for the engineer to know thoroughly his own language and be able to express himself clearly in it, if not by the spoken word at least by the written word. The quality of the English employed in many engineering reports and specifications is extremely poor. The author's arrangements for the recording and filing of engineering matter are very good indeed, and his suggestions seem to me to be one of the most useful parts of the paper. As an instance of the value of research, I can speak from experience of the great usefulness of the research work carried out under the direction of Mr. Wedmore on the heating of buried cables. Before this work was put in hand all information on the subject was scattered and chaotic, it being the result of uncoordinated efforts made by various individuals all over the world. The two reports issued on this particular piece of research have helped both consumers and engineers even more than cable makers, and have given us definite conclusions put forward by an independent authority whose findings have a standing that no private conclusions could be expected to have.

Mr. R. G. Devey: I feel sure that the introduction of research and development departments in manufacturers' works will assist greatly in the manufacture of really first-class materials and plant. A few years ago, the designer in a works produced what he considered to be a suitable design of a piece of apparatus or plant. This was sent in to the works to manufacture and then passed on to the test department, the apparatus being despatched to the user after obtaining trial runs with certain results. It appears now that by the introduction of a development department a piece of apparatus is made up in a rough form and afterwards modified and reconstructed to give as near as possible ideal results, these results being returned to the drawing office. The final designs are then evolved from known results, after which the apparatus is tested and sent to the user. As I am mainly interested in the use and operation of electrical plant, I feel that it will be a great advantage to the user to receive plant which has been thoroughly tried out before and after the final design and before it is despatched and put into commission. The results should be very much more satisfactory when the plant is put into commission, as it must be remembered that failure of any plant in power stations, works or factories results in loss of output. I should be glad if the author would give his opinion in regard to the control of a works development department, as unless this is properly controlled it is quite possible that apparatus may be developed and a good deal of money spent on it, and when finally finished the article is not required on the market. I can quite understand there are many officials in works who might consider that the control should be theirs. The company with which I am connected control their developments by means of a development committee. A useful and broad development committee appears to be necessary and might be formed of an electrical engineer, a mechanical engineer, a steam engineer, a chemical engineer, the technical manager, the production manager and a chairman with a very wide experience and not too young, but with a committee formed of energetic, well experienced younger men. One of the previous speakers in the discussion referred to the system of passing technical papers through various offices in works; if a busy engineer is in the habit of receiving about ten per week he finds it impossible to read them through, with the result that they are generally passed on. Perhaps a more satisfactory method is to circulate abstracts taken from the technical papers. These can be obtained by means of a suitable man who can make abstracts from all the leading technical papers both English and foreign. It is then a simple matter to look through the abstracts and select any particular subjects which might be of interest to each official of the company. The author appears to be very uncertain as to the value of suggestions. I agree that although it is difficult to get the whole of the works employees interested in a scheme of sending in suggestions, this can be done provided the matter is properly handled by the company. When a suggestion is put forward, it should be carefully considered and if it is of no value then the reason should be explained to the suggester. I am informed by the company with which I

am connected that they have received during the past 4 years approximately 2 000 suggestions. Out of these approximately 22 per cent were adopted. The success is in my opinion due to the fact that for all suggestions adopted a suitable monetary reward is granted, the amount being commensurate with the value of the suggestion to the company. Whilst a large proportion of suggestions are useless there is bound to be a large number which when investigated must have some real value. In one case which came to my notice an alteration to the shape of a piece of metal in a particular machine was suggested. This resulted in the output of the machine being increased owing to the number of "spoils" being reduced. The cost was a matter of a few shillings but the company was saved £100 per annum. In another case a suggestion was put forward to make a certain improvement (not a costly one) which enabled the work to be carried out in one operation instead of two. In this particular case the output amounted to several millions of articles per annum. Suggestions of the latter type are most valuable to companies, as they lower the working cost, reduce the capital outlay, improve the efficiency of a works and play a useful part in the balance sheet. I should like to suggest to the author that whilst better work and results can be obtained in a development department, there appears to be little hope of obtaining results such as are obtained in works using plant continuously after it has been installed. Results obtained in a development department must of necessity be only short-period results, and whilst apparatus is probably tested to destruction the results in ordinary use may be considerably different. It rather points to the fact that there should be some form of co-operation between manufacturers and users of plant, and I have in mind that most large power stations and large works keep a history log of each important item of plant in which the working results are entered from time to time.

Mr. A. E. Malpas: The opening statement in the paper emphasizes the changes that have taken place in electrical development in the past 40 years. Reference is made in the paper to Faraday's work, and it happens that exactly 100 years ago he produced chlorine and liquefied it in a closed glass tube, using the chlorine hydrate as a carrier. It has taken almost 100 years to develop liquid chlorine, which has had to wait for the employment of electrical methods in the chemical trade for its application in industry to become a practical and paying proposition. A few figures relating to the German production of chlorine by electrolytic methods may be of interest. Ten leading German works last year produced by electrolytic methods 6 600 tons of chlorine per month, of which quantity more than 33 per cent was liquefied, so that the daily output of liquid chlorine in Germany is probably over 80 tons per day, which shows that their industrial population must to a large extent be fully employed. With reference to the remark on page 72, in the case of a particular installation working at 60 000 volts the insulators were fixed to their pins with litharge and glycerine, which in course of time expanded and caused the insulators to crack. Can the author state what was the particular trouble in the case of the transmission lines of the Lake Coleridge system ?

Mr. C. Rettie: The recommendation that the knowledge of foreign languages should be cultivated is very important. The late Silvanus P. Thompson was a great linguist, and we owe much to him to-day for the knowledge which we possess in more than one scientific branch. I do not wish to question the work done in the laboratory, but it is only by the study of work done by others that any real advance can be made and in this connection the knowledge of at least one or two foreign languages is essential. I should like to add to the author's Bibliography, "Record of Science," by Wm. Warner Bishop, published in *Science*, 25th August, 1922.

[The author's reply to this discussion will be found on page 101.]

North Midland Centre, at Leeds, 27 November, 1923.

Mr. W. M. Selvey: The paper deals with the link between what is ordinarily known as "research," and the process of producing a finished article. For years I have had experience in that kind of work, and have generally found it to be quite unorganized. It is only of late years that an organized system has been employed. The workshop staff in the past have often met with difficulties in translating the ideas of the drawing office into practice, and the result has been the development of what was often known as the "trouble engineer." The experience of this engineer was then fed back to the drawing office. Now it is beginning to be realized that in many classes of smaller apparatus such trouble can be anticipated and corrected before the article leaves the works. Those of us who have been connected more particularly with "Supply" than with "Manufacture" may feel entitled to claim that industry has largely borne the burden and heat of the day, and will, I think, continue to carry some of the load, even if organized research on the author's plan becomes common. On large generating plant and switchgear the supply industry alone can provide the necessary conditions under which important research can be carried out at all. I have in mind the recent experiments at Carville. There is a little difficulty in the author's idea of linking research and development. Sir John Dewrance, in his presidential address to the Institution of Mechanical Engineers, expressed the view that most patents are worthless. Yet the modern stimulus to individual effort often lies in the idea of a sudden discovery and a successful invention that will change the inventor's position rapidly and completely. However idle this idea may be, yet it often remains a fact that even after many co-operative workers have produced by their efforts a fairly satisfactory article, some brilliant suggestion is made which turns it from a qualified to

a complete success. What is the proper reward for such work? If it is nothing beyond the steady salary and the satisfaction of self-sacrifice in research laboratories, then I think that the most individual and brilliant man will still endeavour to work independently. To offset this difficulty there is, however, certainly the asset of preventing the production engineer from dabbling in petty research on his own account, thereby wasting time and money, as has far too often been the case in the past.

Mr. W. H. N. James: It seems to me that if the engineering industry is to make progress in the future we must employ technical and scientific men and use technical and scientific methods to a much greater extent than we have done in the past, and I feel that the importance of this point of view is not often realized. Further, I think there is need to educate the public mind in regard to the value of technically and scientifically trained men. I was very interested in the author's remarks in regard to the qualifications of the research man, particularly in connection with the statement that the man should have the ability to refer matters to first principles. I think that a good many engineers do not realize how very helpful first principles are; a knowledge of first principles, combined with the necessary faith in them, often saves much work or doubt. Occasionally, of course, we may find that the first principle is not effective, but that means that a new discovery has been made. I wish to endorse the author's remarks with regard to the need for completeness in the recording of observations. Definiteness is important, and in this connection the author states that the standard test of a fuse is to connect it across the mains with the containing case connected to the positive, and then to close the switch. This is an example of indefiniteness; the test would be very severe if made near the power house, but much less so if made a considerable distance away. The author states that pure research has been largely done by workers in university and similar laboratories, and I think that technical research also can be done there to some extent if the requirements are made known. In that case, of course, co-operation between the works and the university laboratories is essential, and I feel that there is room for much greater co-ordination between the two classes of workers than often exists at the present time. With regard to the method described by the author for obtaining the time of operation of switches, I had occasion some time ago to test an overload relay. This relay worked off a current transformer, the full secondary current of which was 5 amperes, so that 10 amperes on the relay corresponded to 100 per cent overload. The test was made by taking a double oscillograph and connecting one strip so that current waves through the relay were shown from the moment of closing the switch, the other strip being connected to give a movement when the d.c. trip circuit contacts were closed on the relay. The load on the alternator was very small compared with its total capacity, so that no appreciable change in speed took place on closing the switch, and by taking photographic records and counting the number of waves occurring between the closing of the switch and the closing of the tripping contact, the time of operation was found with considerable accuracy. The lantern slide exhibited by the author showing a galvanometer room, prompts me to ask if he can recommend a type of galvanometer lamp which, while not being too expensive, will permit of use without making it necessary to darken the room materially.

Mr. A. F. Carter: I should like to ask the author what is the relation between the drawing office and research departments. The paper appears to imply that the drawing office has the final word in design, and this may not be advisable. Much could be done by the research department guiding the drawing office in such a point as accessibility. If the draughtsman had to spend, say, a fortnight per annum on practical work in the pit bottom, boiler house and such places, he would no doubt remember the difficulty and would design accordingly.

Mr. S. D. Jones: The building up of the finished apparatus as shown by the lantern slides is a striking illustration of common sense applied to the operations of science. The author lays great stress upon the research engineer, but I feel that a great deal of the success in the examples shown was due to the draughtsman, who would often be still more successful if he were more in touch with the men who had to operate the apparatus. One is often impressed by the simplicity of the final result as compared with the initial design. The plan of perfecting a design before putting it on the market is, I think, the right one, and is the method employed at the Ford motor works. I think that one great secret of success in making plant and apparatus lies in all those who have to handle it being thoroughly familiar with its working; and I consider that Ford's method of training his apprentices is the right one. They enter his training schools at 16, and everything they do in calculations or model- or pattern-making has some direct bearing on the work of motor making and is utilized in the works. Though at school, they are paid for the work which they perform, and thus a sense of reality is given to everything that they do. It has been said that ideas are evolved in England but that very often the Germans develop them and bring them to commercial success. For instance, aniline dyes were first brought out by Sir William Perkins, but chiefly the Germans have developed them. One reason for this state of affairs is that the Germans have a more orderly mind and a greater power of organization for working out things in detail. There is, however, another factor. The author makes a great point of co-operation. In the past the practice of obtaining expert workers at a low salary has been too prevalent; and I once heard the manager of a large works remark that when he wanted a designer for his plant he engaged a "tame mathematician." This ungenerous spirit towards the man of a "brainy" type, who in many cases is not so capable of looking after his own interests as the commercial man is, militates against true development of design in machinery and apparatus. Every type of intellect is required to bring our industrial operations to a higher pitch, and even the ordinary fitter at a bench can give ideas to the research engineer. I think that the author attempts to define too closely the different types necessary to carry out the work of development. This is not practicable with the British type of mind, which refuses to be put into cast-iron compartments. Any suggestion,

no matter by whom it is made, should be tried for what it is worth and, if useful, should be recognized, not necessarily in money, but in some fitting manner. If that were more often done, a greater advance would be made in the industry of our country.

Mr. R. M. Longman: With reference to suggestions from workmen and members of the staff re improvements in method, etc., I have heard complaints from various works of suggestions being adopted without the slightest acknowledgment to the authors of the same. I think that some acknowledgment, whether monetary or merely verbal, would be much appreciated. The author refers on page 64 to a new reversible steam turbine, and I wonder whether it is the same idea that was mentioned to me some years ago. The device would probably work, but undoubtedly with a very low efficiency. It is essential to get the views of those who have to operate the apparatus, as the latter must not only be correct electrically but also of correct mechanical design. It is also essential for research engineers to study both the failures and the successes. The correct idea may be present in the failure, and it may only require proper details to convert the failure into a success. I was very interested in the author's views regarding the keeping and indexing of notes; this is most essential, for although a subject may be fresh in one's mind while one is actually engaged upon it, with so many things supervening it is impossible to carry the details in one's head. I agree with the author as to the use of brick foundations instead of concrete. In some cases it is even advisable to insert a thick layer of rubber.

The Author's Reply to the Discussions at London, Newcastle, Birmingham, Liverpool and Leeds.

Mr. W. Wilson (*in reply*): Before considering the points raised during the discussions, I should like to express my appreciation of the support that the paper has received from the many authoritative speakers in London and the Local Centres. Quite a number of statements and arguments had been included in the expectation that they would meet with considerable opposition, and the sympathetic hearing which they have received has been the more gratifying on this account.

I propose to deal with the discussion under various heads, as follows:—

Scope of the subject.—A number of speakers have criticized the scope of the paper as being either too wide or too narrow; a note as to the former was, however, made in Section XIV ("Conclusion"). It should be pointed out, first, that the intention has been to appeal especially to those manufacturers who have not employed organized development or research, to supply them with arguments why they should do so, and, as far as possible, to provide the information and data needed for such an undertaking. In this, a firm of moderate or small size that would require or prefer to start in a small way was particularly borne in mind. Thus the scope has been made much more comprehensive than will be in order for a larger and more experienced firm that may subdivide and specialize, as indicated by Mr. Fleming. Secondly, the arguments and principles have been illustrated by examples of development from my own personal experience, which has included shell fuses and switchgear, as was explained and set out on page 63. I entirely agree that the exact scope, curriculum, and procedure of development vary according to the type of product developed, as has in fact been clearly stated by Mr. Paterson, and indicated by Mr. Fleming. It will be to the benefit of the industry if this paper is followed by others on the development of specific types of apparatus, of a different nature from switch and control gear. The latter, however, forms a useful example in that full-size models are in general readily made and modified, and thus the full course of development is possible in the laboratory itself.

Nomenclature.—Several suggestions have been made as to the definition of terms employed in connection with research. In addition, minor disagreements have been expressed with statements in the paper, and these have in a number of cases been due to differing interpretations of the terminology. For example, Mr. Paterson objects to my account of the genesis of an idea; but, nevertheless, I find myself in cordial agreement with his statement of the case. Vagueness in the meaning of terms is inevitable in connection with a comparatively new subject, and confusion at this stage is the usual experience. With a view to clarifying matters somewhat, therefore, I venture to express my preference for the terms "Primary or Fundamental," "Secondary or Applied," and "Tertiary or Technical," for the three orders of research as described in Section II, leaving the compact but unsatisfactory term "Pure" out of the list. Scientific research I would define as research in science as distinct from research in history, law, etc.; industrial research as that carried out in association with industry; philosophic research as that undertaken purely for the extension of knowledge; and utilitarian research as that having for its object the acquisition of knowledge of direct benefit to mankind. It will be observed that the last two terms are antithetic, but none the less they differ essentially in motive alone. According to these definitions it is actually possible for a research to be both industrial and philosophic; for it is conceivable that an industrial organization may on occasion permit a research worker to satisfy his own personal inclination in pursuing an investigation along a by-road that promises no immediate financial advantage. It will also be noted that I have used "Development" in Section II, to denote only the "Tertiary" order of research, and do not at all intend the "Primary" to be restricted to non-industrial establishments, the procedure in Section II having indeed been qualified as merely "typical." It is, however, impossible for an isolated works research

department to confine itself to one of these three orders of research, whatever may be the principal object of its existence. I must confess that I do not care for the term "grade" employed by Mr. Creedy, although he has not imparted any ulterior meaning to it. I have, however, heard a speaker stigmatize research connected with a works as "low grade," as compared with "high grade" work done in a collegiate institution. It should be recognized that the whole process of producing a new article, wherever it may be conducted, is carried out by the application of the same principles, by the same type of men, and, as Dr. Garrard has pointed out, by men requiring the same standard of intellect. For these reasons I cannot help regarding this use of the work as offensive, and would prefer to substitute "type" for "grade." Apart from this point I am quite in accord with Mr. Creedy's classification, which amplifies my remarks on this heading.

Relationship between development department and factory organization.—I have been asked by two speakers to formulate the relationship between the development department on the one hand, and the drawing office and other parts of the factory on the other. The general principles should be intimate contact, willing collaboration, and absence of red tape; and the general attitude of the development staff should be that of consultants, who afford advice, information and data when requested to do so. The exact nature and scope of the inquiries depend on the individuals and on the staff organization at the particular factory, but definite rules may be laid down for all cases. These are, first, that communications should be as direct and informal as possible; secondly, that any suspicion of a "superior" or "highbrow" demeanour on the part of the research men must be carefully avoided; thirdly, that problems should, as far as possible, be solved in collaboration with the inquirers, and due credit carefully given to each participant; and finally, that the conversations should be such as to encourage the originating talents of all parties. The last is of especial importance, as has been stressed by Dr. Garrard, for it should now be possible to stimulate such originality and turn it to greater advantage. Section leaders in the drawing office, foremen in the shops, and higher staff members, should be permitted to apply directly to the department, without other formality than the issue of an official report by the latter after the conclusion of the work.

Freedom of communication is of especial benefit to the development staff themselves, for they cannot hope to solve difficulties beyond the powers of the men that are actually doing the work, unless they are completely in touch with this in all its aspects. As has been aptly expressed by Mr. Dunsheath, "where there is contact, there must be fusion and not a fence"; and the same principle has been stated by Mr. Leeson. It is necessary, however, to determine a boundary line, even if it be not rigidly observed, between the functions of the drawing and designing offices and those of the development department, to ensure that the former do not transfer much of their own work and responsibilities to the latter. There are various opinions as to where the distinction should be made, but my own contention is that all routine designing should be done by the factory staff, the word "design" being intended to mean the production of an article from data in hand. Thus a development model is not a design to be merely transferred to paper by the draughtsmen, but is the embodiment of data from which this design can be and should be produced. On the other side of the line, the provision already laid down in the paper and strongly endorsed by Mr. Fleming and Mr. Selvey may be repeated, viz. that all experimenting must be carried out by the development staff. The reasons given in the paper for this rule have not been controverted by any speaker, although the conclusion seems rather to have surprised some members.

A specially close relationship of the same kind is necessary with the routine test-room, for the reason that valuable data as well as inspirations are derivable therefrom. The development staff may be made responsible for the nature of the tests, but, as Mr. Williams has stated, must not be responsible for the carrying on of this section. Development and routine work require different classes of men, and the two functions do not blend. The procedure involved in a typical case would thus be as follows:—The request for information or assistance is made directly by the member of the factory staff requiring this, to the development department, preferably in the form of a note, a duplicate of which may be forwarded elsewhere if so stipulated. Unless the matter is sufficiently simple to admit of a straight-out solution, the appropriate research worker gets into touch with the inquirer and, after discussing the matter fully, carries out the necessary investigation, inviting the inquirer to be present whenever an experimental result is being obtained that would be likely to interest the latter. Upon a conclusion being reached that satisfies the original request, the report embodying this is compiled and sent in. Finally, the drawings (if any) that are got out in accordance with the data supplied are submitted to the development department for endorsement before being proceeded with. This last step complies with Mr. A. F. Carter's opinion as to the drawing office having the last word.

As to the line of demarcation between development and "pure" research, I think this has been stated very clearly and broad-mindedly by Mr. Paterson. I do not consider a development department in general to be the right place for the carrying out of long mathematical investigations; for although I would specify for item $A(1)$ in the training scheme on page 66 a course in mathematics including analytical conics, differential and integral calculus, and elementary differential equations, yet the development worker would ordinarily have too little of this work to do to retain sufficient facility in carrying it out. Hence, when a "pure" research department is available, such work should typically be forwarded to it for solution.

Finally, it must be made clear that the promotion and maintenance of co-operation and concord between the various departments is in the hands of the management. The whole success of a research department in particular depends upon the maintenance of correct relations with the rest of the works, and if this matter

be neglected by those in high authority, efficiency and harmony are impossible. The ideal state of things is for each component to contribute its own share to the work without trespassing on the domains of others, and firm direction alone can bring this about.

Control and jurisdiction.—The question as to who will decide whether any particular item of development shall be undertaken, and whether the resulting product shall be manufactured, has been raised by Mr. Creedy and Mr. Devey. There is no doubt in my mind that the decision as to these points must rest with the management, on the principle that he who pays the piper can call the tune. But the control as to the first point should be of the most elastic possible description, as a research worker is at his best when he is given free rein. With regard to the second, commercial considerations play a great part in the matter. If, however, the development man has gone about his work thoroughly, he will have qualified himself to speak with a considerable degree of certainty on this question, and his opinion should be treated with due respect. For psychological reasons, the shelving of the results of an arduous and successful investigation should be avoided as if it were an actual loss, although the attention of a busy manager may be required when his interest is attracted elsewhere. Mr. Ford's statement that "there is never any demand for a new thing" is widely applicable, and its truth should be borne in mind even by those who will actually profit by the adoption of new proposals. We have it on the authority of Dr. Mees that "It is by no means easy to prevent work which has a real bearing on practical questions being ignored by the practical man to whom it should be of value. The mere filing of a report is not always sufficient, and some method of following up the application of the work is desirable."

With regard to administration, I agree generally with the scheme described by Mr. Devey.

Relationship with the user.—It is natural that the presence of so many supply engineers at the various discussions should bring about many references to the user's point of view. The purchaser is concerned with both ends of the process, for he must be satisfied before he places an order, and he gives the final verdict upon the product after it has been put into service. The great amount of development work carried into effect by users is readily acknowledged, and the establishment of closer relations, to enable greater co-operation to be attained in the future, is hoped for. The sales organization of an engineering firm is the usual medium whereby contact is established and maintained with users generally, and liaison with the former is promoted by the regular supply of information from the development files. Many of the reports are specially written for circulation to them, and most of the rest are indexed in a monthly list, which is circulated to the various branches and from which they can be selected and asked for as required. This will answer Mr. Leeson's query. The close touch advocated by Mr. Creedy, Mr. Devey and others is a most advantageous state of things. It is my own practice to visit users personally in order to secure at first hand the data so obtainable. The valuable nature of suggestions from users has already been mentioned in the paper; and the assurance can be given to Mr. Lawson and other speakers that no criticism from this source is ever treated lightly under my own auspices.

Invoking and dealing with suggestions.—A considerable amount of discussion has been caused by the reference in the paper to the value of suggestions. Like Mr. Fleming's, my own experience of suggestions from the works has not been a very favourable one, as although there is a standing offer of a reward for suggestions adopted, and although such rewards have been given in the past, yet the number of suggestions, useful or otherwise, is very small indeed. This coincides with the experience of the various public Suggestion Boards instituted by the belligerent nations during the war. It has, however, always been my own opinion that the man who is in the best position to make novel suggestions regarding a given operation is the man who is actually engaged upon the work. For example, the machinist should be more likely to discover an improvement in the method of machining than the tool setter, and the tool setter more likely to arrive at an improvement in the tools than the foreman, and so on. Consequently, I was particularly glad to note from the remarks of Mr. Williams and Mr. Devey that it is possible to obtain better results than I have hitherto heard of. I have now no doubt that an atmosphere favourable to invention can be created in the workshop, just as in the design and drawing offices and the development laboratory itself. The system has one or two minor drawbacks, as, for example, when a workman makes a suggestion as to an obvious measure in connection with a new product, which would have occurred to practically anyone and will have almost certainly been already acted upon by the drawing office. Upon the appearance of what appears to be his idea in a concrete form without acknowledgment to himself, he is likely to feel aggrieved, and consider himself badly used. Mr. Devey's method of submitting suggestions to a committee which includes representatives from the workmen themselves would appear to overcome this trouble.

The existence of the development department offers a new means of putting into effect suggestions from various parts of the works. In the past, there is no doubt that would-be inventors have been discouraged, because the trying-out of their suggestions would involve trouble to people who are already loaded with routine duties. Now that the extra work will not fall upon the factory officials but upon the development staff, it should be possible to increase the number and the value of suggestions from the factory generally. With regard to the nature of these suggestions, Section VI of the paper has not been strongly challenged, and I adhere fully to what has been stated therein. Mr. Baker's expectations from "any intelligent artisan" need not, I think, be taken very seriously.

Qualifications and training of staff.—Many speakers have referred to the section dealing with qualifications and training, and have given additional opinions upon this important subject. Mr. Wedmore's preference for a youth who has from his boyhood shown signs of a creative mind and has been accustomed to make things for himself, appeals to me very much, and I consider

this aptitude to be a sure sign that the youth is of the right material. The value of making things has also been mentioned by Prof. Marchant. Like him, I consider this to be one of the most promising traits in the character of a budding engineer, and one that will also stand him in excellent stead when he goes into the works to obtain his real experience.

Mr. Melsom and one or two other speakers have stated that a university degree is not essential, and I would draw their attention to the wording of the paper on this subject, especially the use of the expression "of university status," and also the deduction that "a university degree *or its equivalent*" is indicated, in Section VI. I should be far from attempting to show that a degree is the only reliable proof of a research worker's fitness for his duties, or even that a university is the only place where the qualifications stated in Section VI can be obtained. What I do say, however, is that a youth of to-day who considers that his talents lie in the direction of research, and who wishes to fit himself for this work, should by all the means in his power endeavour to secure the necessary training by taking such a degree. Mr. Higgs's support of this standpoint is especially appreciated. It should not be overlooked that, in Section V, I have laid down stringent rules for the practical experience a research man should have, in addition to his theoretical training.

Prof. Marchant has referred to the language training which forms part of my curriculum, and mentioned that some famous investigators in the past have not been gifted in the direction of lucidity of expression. However, in the functions which a development worker has to fulfil, I consider that this qualification is of special importance, as he is there largely to afford useful information to the staff of the factory and its outside organization. This he cannot efficiently do unless he is able to put his meaning into easily understood language. Mr. Rettie has also pointed out the great practical advantage of having access to information which may have been published in foreign languages.

In my curriculum I had intended "Applied Electricity" to be included under "Electrical Engineering."

Facilities and conditions for research.—The great facility required for development is, as Mr. Wedmore has said, that for making real tests. Some of these may appear to be unduly expensive or troublesome when proposed, but all my experience goes to prove that it is far cheaper in the end to make them in the laboratory than to suffer for their omission afterwards. The value of incentive and credit to research workers has been rightly emphasized by Mr. Woodhouse and Mr. Williams.

Mr. Selvey has referred to the importance of anticipating trouble before an article leaves the works. This policy of anticipation is the great feature of technical research work, and is most valuable when it prevents trouble before the articles reach the routine test-rooms or even the drawing office. This can be readily accomplished when the development work is continuous, as distinguished from "hand-to-mouth." If no communication is made with the development staff until trouble arises, and if the whole case has then to be inquired into and digested, the necessary data secured, and the investigation carried out, under these conditions all has to be done in the shortest possible time, and thus at the greatest possible inconvenience and at the lowest efficiency. If, however, the department is continuously supplied with manufacturing data and details of performance by the rest of the works, as laid down in the first column of page 64, then these panic conditions are very largely obviated; probable defects are anticipated and their remedies proposed, probable wants are foreseen and satisfied, and, in general, most of the trouble is intercepted before it has caused waste of time or materials.

Remuneration of research workers.—The question of payment for research was not dealt with in the paper, but has been broached by quite a number of speakers. While agreeing in the main with what Mr. Selvey and others have said regarding payment by results, I do not think that anything resembling "piecework" remuneration is practicable in the case of investigators, or even desired by them. On the one hand, they are not a mercenary class, and the most powerful incentive that can be given them is practical appreciation of the results of their work, in the shape of utilization and verbal acknowledgment. On the other hand, they recognize that it is their function to make discoveries and inventions, and that this is covered by their salaries. The appropriate way, then, of paying by results, is to adjust the salaries from time to time as their value to the firm increases. This scheme should not, however, prevent the award of an occasional bonus when a piece of work of special advantage to their employers has been effected.

With regard to the amount of the salaries, I welcome Mr. Wedmore's statement that an engineering business should have development engineers among the most highly paid members of its organization. The practice mentioned by Mr. Jones of referring to their kind as "tame mathematicians" is comparable with the traditional refusal on the part of a successful manufacturer to send his son to college, because he could "buy all the brains he wanted in his business for three pounds a week." Such an outlook is a suicidal one, for an investigator is utterly incapable of exercising his mental faculties efficiently if his mind is already occupied with financial worries or discontent, or is not afforded adequate relaxation. There are few other professions in which the output is so directly influenced by the input as in the case of industrial research, and generous treatment is therefore a matter of policy as well as of ethics.

Industry and the universities.—It has been generally agreed that greater co-operation between the universities and industry will be productive of nothing but good. Each has its special sphere for research work. The calmer atmosphere of a college laboratory, and a liberal provision of philosophical instruments, conduce to thoroughness of consideration and of experimental proof; while the activity of a factory and the accessibility of large apparatus and supplies of power induce enterprise and practicalness. As has been pointed out by Prof. Cramp and Mr. Combes, there should be no fear of harmful overlapping on this account. It is not, in general, possible for a college to carry out

development work for a manufacturing firm, partly because this species of research chiefly deals with those features of the firm's products that are peculiar to itself, and which it would therefore be least willing to share with competitors. A certain amount of secrecy is therefore necessary, which under ordinary circumstances would not be practicable in a teaching institution. This is, however, actually carried out in the United States by the Mellon Institute's scheme of industrial fellowships, described in some detail in "Research and Industry" (see Bibliography), and briefly by Mr. Kilburn Scott in his contribution to the discussion.

In reply to the inquiry of Mr. Malpas, the insulator trouble in connection with the Lake Coleridge hydro-electric scheme, overcome at Canterbury University College, was due to porosity of the porcelain, which was only made evident by subjecting the material, while immersed in a dye, to a pressure of 1 500 to 2 000 lb. per sq. in. for a period of 7 days.

I am much interested in the question raised by Prof. Cramp of providing works experience for students as I have twice formulated schemes for this, under radically different circumstances, both of which gave results entirely satisfactory to the parties concerned. My convictions are expressed in the following conditions. On the part of the students, there must be a real determination to play their part in the works, by identifying themselves for the time being with their fellow workers, laying "swank" on one side, doing, if anything, more than their share of the work, and not asking for any privilege that is denied to their companions. On the part of the firms, there must be a greater willingness to take in men who agree to the above, to give them the highest justifiable responsibilities, and to afford them an interest in the work by paying them something of what they are worth. I am not overmuch enamoured of the usual "pupil" course, on account of the large element of privilege inseparable from it, which not only reduces the value of the experience but also largely cancels the value of the youth to the firm. Thus the number of such appointments that an undertaking is willing to make is seriously limited; and an appointment tends to become a favour to be conferred on those having special claims on the firm.

The principle of putting newcomers to a works laboratory into the shops for preliminary experience I regard as being sound in every way.

Co-operation and co-ordination.—The value of co-operation and the need for its fullest possible extension have been generally endorsed, and I particularly welcome Mr. T. Carter's remarks in this connection. Speakers in every Centre where the paper has been read have expressed appreciation of the work of the Electrical Research Association, not only in carrying out valuable research work on its own account but more especially in promoting co-operation between manufacturers, universities, and power supply authorities. In numerous fields of electrical work, economy and increased reliability have already resulted directly from its work, notably in the safety of mining apparatus, underground and overhead transmission, insulating materials, and high-tension switchgear. I was particularly impressed with the success of the negotiations with the supply authorities at Carville, and with the thoroughness, care and ingenuity that characterized the tests upon makers' own oil switches there. The data cannot fail to be of great assistance to designers, and it is to be earnestly hoped that these tests will be proceeded with on an increasing scale as regards breaking capacity. The Association is rapidly becoming essential to the whole electrical industry, and deserves the full support of every constituent member.

When the co-operative principle is pushed to its furthest limit, it includes co-operation between engineers of different nationality. I see no harm, but good, in the interchange of designs as mentioned by Mr. Fleming, as long as it does not lead to deterioration of initiative on our part.

Secrecy versus publication.—Where the motive for the abandonment of secrecy is the furtherance of co-operation, I am in agreement with those speakers who advocate publication. That the firm with which I am connected is not ungenerous in this respect is made evident by my having been enabled to write the present paper, as well as that on liquid rheostats and several articles in the technical Press, publishing data that had been obtained at considerable expense; and I think their generosity deserves this acknowledgment. One cannot help suspecting, however, that the desire to get something for nothing sometimes actuates those who denounce secrecy. I have remarked above upon the impossibility of giving away all the results of development.

Small firms and research.—As Dr. Kahn has pointed out, development was assisted abroad by the earlier organization of industry under the auspices of large firms. But I think that Mr. Collie and Mr. Meyer exaggerate the position when they assert that research is only possible for a big concern. A numerical instance may help to make this clear. Let it first be supposed that a small firm risks putting a new development upon the market, and manufactures a batch of 50 articles; and, further, suppose that their judgment was at fault, the market absorbing these only with difficulty. In this case the firm has incurred no other loss than the abandonment of its design. But if a larger firm be supposed to have turned out the same article, to the extent of 500, then if only 100 were sold (the market being the same for both firms) they would now incur an additional heavy loss due to the serious amount of dead stock that must be written off. Thus the smaller the firm, the more flexible and enterprising it can be, and therefore the more it is likely to gain from development. The cost of the latter can be borne like any other overhead charge. It is the rule in such cases, as Mr. T. Carter has pointed out, for one of the heads of the firm, such as the chief engineer or even the managing director, to superintend development work personally, and in this way the financial conditions are met.

Research work during slump conditions.—There is no difficulty in proving that development work should be carried on when trade is good, but opinions are certainly not unanimous as to its furtherance in times of slump. The natural tendency on the part of financiers would be to reduce it then to a minimum, in common

with other overhead expenses. But if it is of advantage, when times are good, to remove all non-standard work from the shops, and worry and uncertainty from the designing staff, it is surely more necessary to do so when times are bad, and when not only is economical working in the factory specially desirable, but also many special orders have to be entertained, each requiring individual attention. These arguments would seem to indicate that development work should be increased during slump conditions, and this is actually what Mr. Pearce's suggestion of "load equalization" amounts to. Surprising though it may be at first glance, the latter policy is the correct one. It should be realized that the effect of development work is lasting, and does not vanish when the articles that originally called for the particular investigations are sold. Research is thus equivalent to the putting by of capital, and capital that will return a high rate of interest. A slump should therefore be regarded as a time of storage, and a fund should be reserved for this special purpose. In addition, an extra value is attached to slump research, as it is carried out under conditions of stringency and therefore when the research workers are on their mettle. It is well known that other originators, such as poets, musicians and artists, often do their best work in times of stress, and it may well be that a slump is in reality a period of opportunity instead of misfortune.

Standardization, mass production and research.—Mr. Higgs has laid stress upon the necessity for industrial research in connection with repetition work, and Mr. Morton instances the facilitation of research by standardization. It is of advantage, when dealing with any one of these three principles, to realize that all are phases of the same movement. It is most important that research and standardization should go hand in hand, and the introduction of the further principle of specialization results in mass production. I had endeavoured, in the first part of Section V, to prove the importance of development in a factory where nothing but repetition work is carried on, although it might seem to the uninitiated that such a works would not need any form of research.

Cost of research.—The question of research costs has been mentioned by Mr. Fleming, Mr. Pearce and Mr. Leeson, the first of whom gave an estimate of 3 to 5 per cent of the turnover as a fair proportion to be devoted to research. It is a necessary feature in the organization of a department that the cost of upkeep should be placed on a proper basis, and I consider that these figures are about correct.

General.—A few points have been raised concerning accessory details in the paper.

The soundness of getting down to first principles has been endorsed by Mr. James, while Mr. Jones has referred to the frequently surprising simplicity of the final result as compared with the initial design. One learns to value the attitude expressed in both of these opinions the more in that it is not in accordance with human nature. A layman tends to undervalue an investigator's more successful work because of its greater simplicity; his reasoning because it is too childish; his explanations because they are too lucid, his calculations because they are too elementary, his designs because they appear too obvious. Yet the facts are as indicated by Mr. Paterson in "The Physicist in Electrical Engineering" (see Bibliography), that "The better the physicist, the simpler the terms of the explanation."

Mr. Melsom has provided some intimate details for testing fuses, and the same matter has been mentioned by Mr. James. I think they will realize, if they refer again to the context, that the fuse test was introduced merely to illustrate the requirements in design, and consequently it was not in order to dilate upon an unimportant side-issue, when the matter could be summarized with sufficient accuracy by the three lines that I employed.

In connection with examples of development shown in Appendix II, Mr. Baker should note that, as I have already indicated in introducing them, their insertion was not intended to display ingenuity but to illustrate the principles laid down. The feature of interest in connection with the brake pulley in Figs. 2 and 3 is again not this method of absorbing power (which was familiar to some of our grandfathers) but the device employed for injecting and ejecting the cooling water with the certainty of avoiding a mess.

In reply to Mr. Leeson, the oil-testing apparatus in Fig. 6 was designed for dealing with small samples of oil received by post from distant clients. When a sufficient quantity of oil is available, the more usual apparatus has always been employed. It should be noted that this device was designed and used before the B.E.S.A. dealt with the matter, and was actually included in the paper before the present standard apparatus was published. None the less, I dissent from Mr. Leeson's opinion as to its unreliability. The pressure recorder in Fig. 5 has hitherto been employed principally for obtaining comparative results, and it can be regarded as being perfectly accurate for such readings. Used in this way, the pressures developed by various explosive mixtures, in various pieces of apparatus, employing various relief devices, and with other variations, can be accurately compared with one another, and, if necessary, with the pressure required to burst an apparatus. However, there are no more factors introducing error in it than in the steam- and gas-engine indicators, which are regarded as precision instruments. Consequently, I estimate its absolute accuracy as being within about 5 per cent.

Mr. Leeson and Mr. Parry have commented on the possibilities of error in the instruments on the test board of Fig. 1, due to heating or stray fields. The meters are situated so far from either rheostats or conductors carrying a heavy current that these effects have been found to be quite negligible in practice. The high-reading ammeter is supplied from an instrument transformer at nearly floor level, none of the heavy-current wiring being above the height of the bench top. The accuracy attained with this set is fully equal to the requirements. Instruments are, however, checked on a special bench in a test room provided for highly delicate work, and containing the oscillograph. I agree with Mr. Parry as to the utility of the latter, but in its present forms it is hardly convenient enough for factory work that can be adequately carried out by such apparatus as that shown in Fig. 4.

Mr. Leeson's example of technical research, shown in Fig. A, is very interesting.

In reply to Mr. James's inquiry regarding a galvanometer lamp for daylight work, the practice I am familiar with is to employ a translucent scale, and a gas-filled lamp of the motor-headlight pattern, of 24 watts' capacity and working at 12 volts.

I was interested to find that Mr. Longman had come across an instance of futile development similar to mine in connection with steam turbines. It may, in fact, have been the same case, though the turbine seems strangely susceptible to such misdirected enterprise, and the two are probably distinct examples. Another case almost identical with my own experience was recorded at about the same date in the American publication *Power*.

THE WHIRLING OF SHAFTS.*

By Julius Frith, M.Sc., Member, and F. Buckingham, B.Sc.

(*Paper first received 14th August, and in final form 29th October, 1923.*)

Summary.

The paper is an attempt to explain the phenomenon of whirling by proving that it is essentially a case of vibration and obeys the laws of vibration, especially those relating to the phase change between the disturbing force and the resulting displacement.

Whilst acknowledging that the critical speed of whirling is usually calculated by the same expressions as those which give the natural time of vibration, it is maintained that the identity of the two phenomena is not sufficiently recognized. To prove this, the case of the spring-controlled governor is cited, which, according to the ordinary treatment of whirling—equating the centrifugal and the elastic restoring forces—should come in again above a certain speed.

A description is given of experimental verifications of the theories put forward.

Introduction.

In spite of all that has been written on the whirling of shafts, it is doubtful if the mechanism of the phenomenon is generally understood, and this paper is put forward in the hope of clearing up certain points which may remain obscure after a study of the more elaborate but in many respects inadequate treatments.

Some years ago one of the present authors, in conjunction with Mr. E. H. Lamb, read a paper on the torsional oscillations of shafts.† We now wish to extend a similar treatment to the whirling of shafts, as it has been impressed upon us very forcibly that the usual treatment is inadequate in that, whilst giving correct numerical solutions, it quite fails to explain the mechanism by which the results are obtained.

A very simple example will serve to illustrate our meaning. In Fig. 1, AB represents a vertical shaft carrying a mass M at its centre and supported in spherical bearings at A and B. The shaft is very slightly bent so that on being *slowly* revolved, the above mass would rotate in a circle of radius r. Let the stiffness of the shaft be defined by saying that it would require a force F applied to the mass M to displace it 1 foot.

Exactly the same effect is produced if the shaft is straight and the mass M is slightly eccentric. The distance r would then be measured from the centre of rotation to the centre of gravity of the mass.

Now let the shaft be rotated at a speed of n revolutions per second ($= 2\pi n$ radians per second $= \omega$). The usual textbook treatment of this would be to say that the mass M will now fly out and revolve in a circle of radius, say, $d + r$, and to write

$$M\omega^2(d + r) = Fd$$

from which
$$d = \frac{M\omega^2 r}{F - M\omega^2}$$

and
$$(d + r) = \frac{M\omega^2 r}{F - M\omega^2} + r$$

If the value of this expression is plotted against n, it increases until $n = (1/2\pi)\sqrt{(F/M)}$, when it is infinite, and if the curve is further extended on the assumption that the expression still holds when $M\omega^2$ is greater than F, the value is reduced and ultimately becomes less than r.

In actual fact it is found that the whirling shaft has its maximum displacement when $n = (1/2\pi)\sqrt{(F/M)}$, and that at higher speeds the displacement diminishes to something less than the initial eccentricity. The shaft therefore runs truer at speeds above the critical than at those below. These are results to which those obtained from the foregoing expression bear a superficial resemblance, but it will be shown that at no speed does the expression give the true displacement, and the

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† J. Frith and E. H. Lamb: "The Breaking of Shafts in Direct-Coupled Units, due to Oscillation set up at Critical Speeds," *Journal I.E.E.*, 1902, vol. 31, p. 646.

method of its derivation does not justify its application to the problem of whirling at all.

To those who uphold the treatment let us put this question: The expression as derived being perfectly applicable to half of a very common type of steam-engine governor, is it contended that such a governor would, beyond a certain definite speed, close in again and allow more steam to pass? If so, then here is a most interesting explanation of many flywheel accidents. We have, however, tried the experiment and have ascertained that, for such a governor, the mass M moves further and further out for speeds up to *and beyond* what would be the critical value, so that this handling of the problem, as far as the running of shafts above their critical speed is concerned, is utterly discredited.

Some authors take refuge in some such phrase as "above the critical speed the system tends to rotate about its centre of mass," which, although true as a statement of fact, by no means constitutes an explanation.

It has long been recognized that the critical speed,

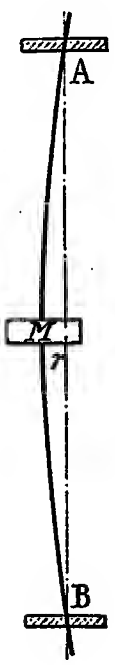

Fig. 1.

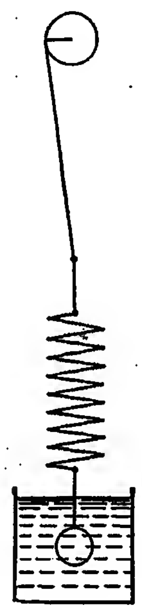

Fig. 2.

as given above, is also the number of oscillations per second at which the shaft would vibrate if plucked like a fiddle string, and this gives the clue to the correct explanation of the facts. For imagine the above shaft not to revolve but to be subjected to a periodic disturbing force of gradually increasing frequency. At frequencies much below the natural frequency of the shaft, these disturbing forces would produce little effect; this would be so until the frequency of the disturbing force nearly equalled that of the system composed of the shaft and its attached mass. When the two frequencies were equal, the amplitude of the motion of the mass M would increase until, if there were no friction, sufficient energy at that frequency would be stored up to break the shaft, or otherwise until the resulting friction absorbed all the available energy.

If, however, the frequency of the disturbing force were still further increased, the amplitude would gradually decrease until, when the force had a frequency many times that of the shaft, the latter would again be practically at rest.

But this description leaves out of account some other very interesting facts, an understanding of which is essential for the other problem. There is, for instance, a change in phase between the disturbing force and the motion produced, and this can be better illustrated by a slightly different example.

Imagine a mass suspended in oil by a spring, as in Fig. 2. If the other end of the spring is moved very

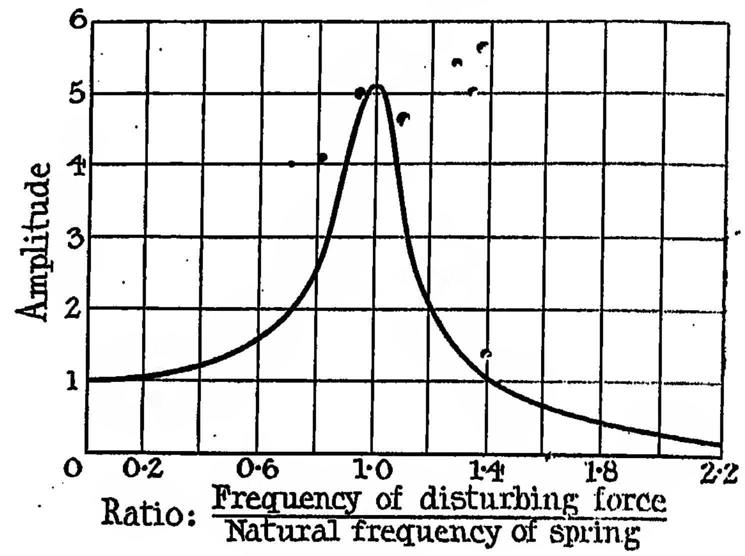

Fig. 3.

slowly up and down, then the mass will move up and down, not only with the same amplitude but *in phase with* the force acting on the other end of the spring. As the frequency of the motion becomes greater, the amplitude will increase and a change of phase will take place between the top of the spring and the mass. If the motion of the top of the spring be caused by the

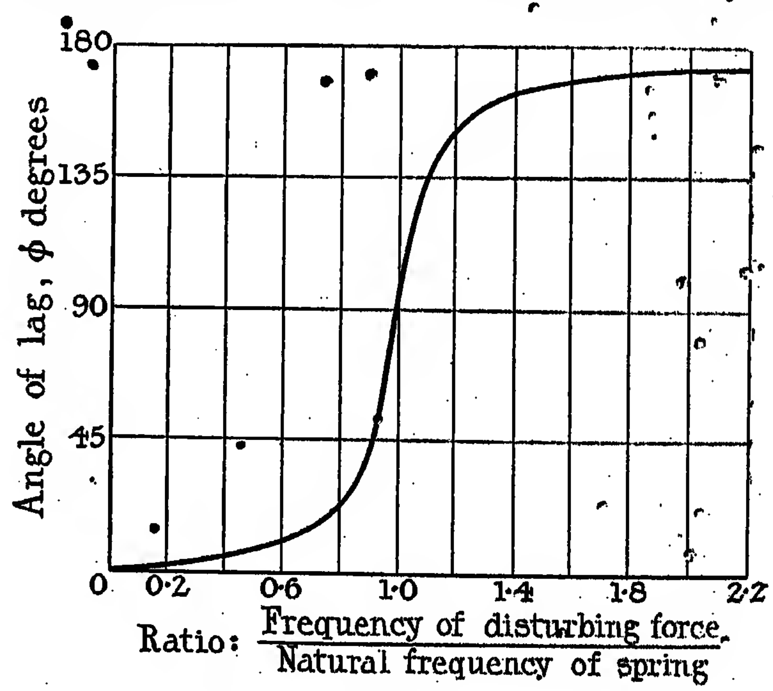

Fig. 4.

rotation of a crank, then the motion will be harmonic and the crank will indicate its phase.

The resultant motion of the mass will also be harmonic and may be considered as the projection of a revolving vector, which will in turn indicate the phase of the motion of the mass.

If the stiffness of the spring be defined as the force F required to extend it by unit distance, then at a

critical speed $(1/2\pi)\sqrt{(F/M)}$ the amplitude will be very nearly a maximum but will not be infinite owing to the friction of the oil. The phase difference between the force acting on the top of the spring and the motion of the mass will now be 90° and will approach 180° as the frequency of the disturbing force becomes greater than the critical value.

The value of the amplitude for a particular case is plotted in Fig. 3 in relation to the frequency of the disturbing force, taking the motion of the crank as unity. This figure cannot represent the gradual change of phase, and it is best, therefore, to neglect sign altogether in this figure and take it from the curve in Fig. 4.

It is generally recognized that there is a resemblance between whirling and vibration, and the usual method of obtaining the critical whirling speed is to calculate the natural frequency of transverse vibration of the system. We propose to show that this coincidence is not accidental, that the phenomenon of whirling is essentially one of vibration, and that only when whirling is so regarded is the stability at speeds above the critical satisfactorily explained.

The Shaft in Transverse Vibration.

Let us set the shaft AB vibrating *in one plane* by applying to it a periodic disturbing force of maximum value x, and study the various quantities involved. The shaft will, of course, vibrate with the frequency of the disturbing force. Call the time of one complete vibration T, the half amplitude A, and the coefficient of friction μ.

The whole state of vibration is maintained by the disturbing force, which has therefore to provide for several different things. It has first to provide a component to overcome FA, the stiffness of the shaft. This component must have a maximum value equal to FA but acting in the opposite direction, i.e. outwards, and the maximum would occur at the ends of the swing, when A is a maximum. Having overcome the stiffness of the shaft, it must provide a component to give the mass M its acceleration. The maximum value of this would be $4\pi^2AM/T^2$, which would also occur at the ends of the swing but would act inwards. Lastly, the disturbing force must provide a component to overcome friction. Not knowing what law the friction obeys, we will write the force to overcome it as $\mu \times$ velocity, which is probably very near the truth. It will have a maximum value of $2\pi A\mu/T$ at the centre of the swing.

Knowing all its components, we can now add them together and find x, the maximum value of the disturbing force. Below the critical speed the vector diagram will be as Fig. 5 (*a*). In this figure the values represent the maximum values of the various quantities, ω being written for $2\pi/T$. The one marked x is the maximum value of the disturbing force. It is seen resolved into its three components, FA, $M\omega^2A$ and $\mu\omega A$, which are all jointly necessary to keep the shaft vibrating.

FA is in phase with A (the displacement) and therefore points to the actual position of the shaft in space, which is seen to be out of phase with the disturbing force by an angle ϕ, the tangent of which is $\mu\omega/(F - M\omega^2)$. This is the angle shown in Fig. 4.

At the critical speed the vector diagram would be as shown in Fig. 5 (*b*) when $FA = M\omega^2A$ and $\mu\omega A = x$. In fact, the amplitude increases until this equality is effected, when equilibrium is established; but for μ, A would be infinite.

At speeds above the critical, conditions would be as shown in Fig. 5 (*c*). It is here seen how far the motion has got out of phase with the disturbing force.

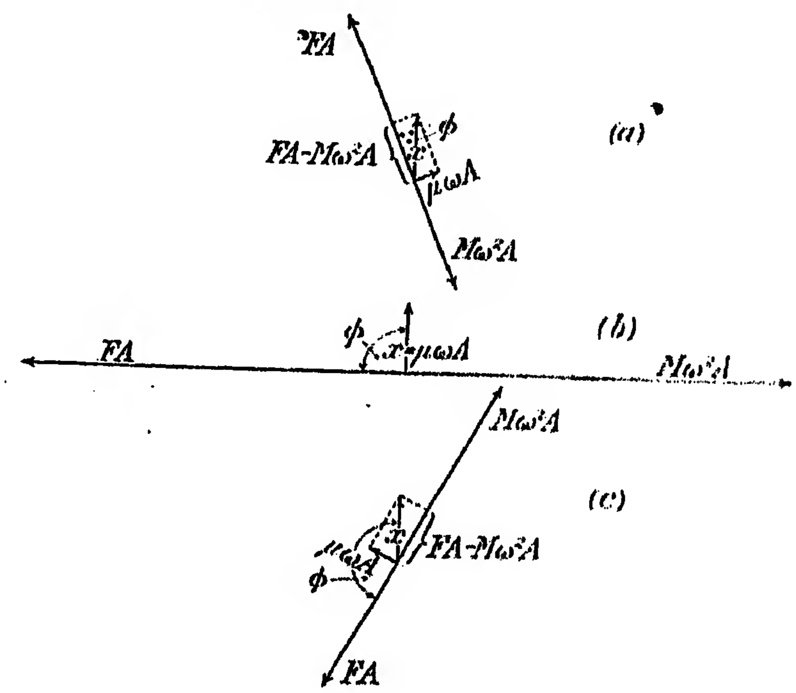

Fig. 5.

If μ is comparatively small, A is a maximum when $\omega^2M = F$, i.e. when $T = 2\pi\sqrt{(M/F)}$, which is of course the time of natural vibration of the system.

From the figures it will be seen that in all cases the following relations hold:—

$$x = \sqrt{[(FA - M\omega^2A)^2 + (\mu\omega A)^2]}$$

$$A = \frac{x}{\sqrt{[(F - M\omega^2)^2 + (\mu\omega)^2]}}$$

The Shaft in Whirl.

If the same shaft AB is now revolved, $M\omega^2r$ will supply the disturbing force, the maximum value of which we have called x.

As the speed is varied, this force varies only as ω^2, r remaining constant. It is the existence of the original eccentricity r which is the whole cause of the whirl; further elastic deflections take place under the combined actions of centrifugal force, the stiffness of the shaft and friction, but all this happens over and above the original motion in a circle of radius r. This is made clear in Figs. 6 [(*a*), (*b*), (*c*) and (*d*). The action of the crank moving the top of the spring in Fig. 2 is now represented by r in circular motion. The motion of the mass is sometimes greater and sometimes less than r, but r is always present in it, even though M ceases actually to revolve at that radius.

The value of the disturbing force due to r is $M\omega^2r$ and increases as ω^2. This force will give the shaft

a circular vibration which may be resolved into two rectilinear vibrations at right angles. In case this circular motion cannot be recognized as a vibration, a very simple experiment will be convincing. Fix a hatpin by its point in a vice or drive it into a bench; it can be set into rectilinear or circular vibration at will, but the rectilinear motion will often end in being more or less circular. If, when vibrating in a circular path, its shadow be projected by two lights on to two planes at right angles, the two rectilinear components of the vibration will appear. As the inverse of this, a harmonograph will combine two rectilinear vibrations into circular motion.

We can therefore write the same expressions as before for each of the two components at right angles of the whirling shaft.

All the quantities which varied harmonically in the case of rectilinear vibrations now become revolving vectors of constant length, pointing to the various positions of the shaft in space. The vector $M\omega^2 r$ points to the original position of M on the bent, unstrained shaft, and Fd to the actual position of the shaft in space.

Regarded from the point of view of the elastic displacement alone, all these vectors revolve from a centre where $d = 0$, d being the elastic deflection of the shaft caused by the rotation—as distinct from the permanent set r. The starting point of d in the actual combined whirling motion is on the circumference of a circle of radius r. Then

$$d = \frac{M\omega^2 r}{\sqrt{[(F - M\omega^2)^2 + (\mu\omega)^2]}}$$

ω is equal to 2π times the revolutions per second and is sometimes called the "circular frequency" of the disturbing force. It is sometimes useful to write α for 2π times the natural frequency of the system, of which the time of one complete vibration, $T, = 2\pi\sqrt{(M/F)}$, M being as before the moving mass and F the restoring force per unit displacement.

The natural frequency $= 1/T = (1/2\pi)\sqrt{(F/M)}$, from which $\alpha = \sqrt{(F/M)}$ and $F = M\alpha^2$.

Making this substitution in the above expression for d, we obtain :—

$$d = r \times \frac{\omega^2}{\sqrt{[(\alpha^2 - \omega^2)^2 + (\mu\omega/M)^2]}}$$

If $[(\mu\omega/M)]^2$ is very small, as it is likely to be in most practical cases, then $d = r \times \omega^2/(\alpha^2 - \omega^2)$.

The actual motion of the shaft in whirl is a circular vibration compounded of two of these rectilinear vibrations at right angles, plus the rotation in the radius r due to the shaft being bent; the radius R of the path of M through space being compounded of d, the half amplitude of each of the two vibrations, and r, the original eccentricity, which causes the disturbing force, these two being at the angle ϕ to each other, as shown in Fig. 6.

The application of the various forces is of course on the mass M, the restoring force of the shaft along the line d, the centrifugal force which is compounded of the disturbing force $M\omega^2 r$ and the acceleration to the centre of vibration $M\omega^2 d$ radially along R. Similarly, the total frictional force is circumferentially at right angles to R.

The frictional resistance is $\mu\omega R$ and has a moment $\mu\omega R^2$ round the centre of turning, this moment being counteracted by the torsional stiffness of the shaft. If we express this as the torque required to twist the shaft through 1° and call it f, then the friction will cause the shaft to twist through an angle

$$\frac{\mu\omega R^2}{f} = \theta \text{ (say)}$$

This angle will, in general, be very small.

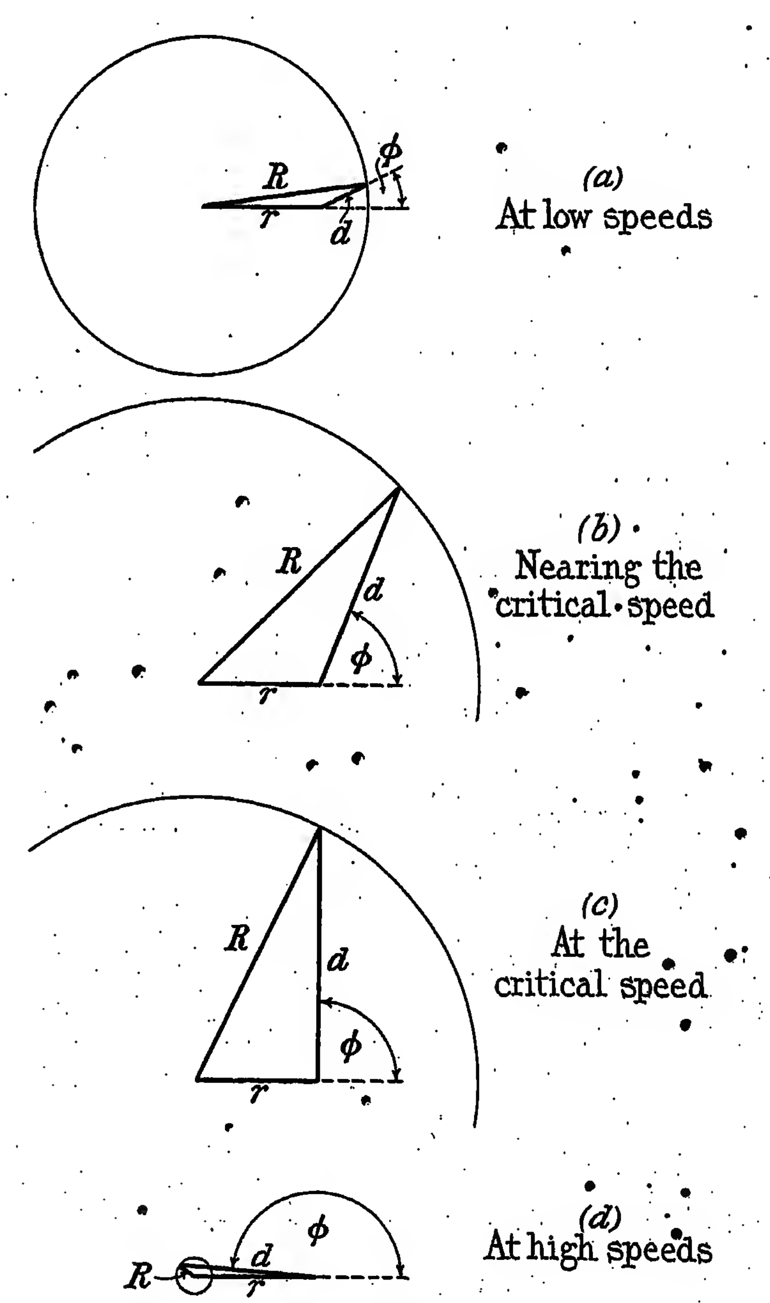

Fig. 6.

The energy to overcome the friction will be derived from the prime mover, as from it comes all the energy to maintain the state of vibration.

We can now represent in a figure the shaft in whirl at various speeds, all at the same angular position, say, when the disturbing force $M\omega^2 r$ (which is due to, and in phase with, the original eccentricity) acts in one particular direction (see Fig. 8).

A numerical example may help to make this clear.

Let $M = 100$ lb.
$F = 10\,000$ poundals per foot of deflection.
$r = 0\cdot01$ foot.
$\mu = 500$, i.e. it would take a force of 500 poundals to move M at 1 foot per second.
$f = 1\,000$ foot-poundals per 1° twist.

Then d, the elastic deflection due to being revolved at ω radians per second, would equal

$$\frac{100 \times \omega^2 \times 0\cdot01}{\sqrt{[(10\,000 - 100\omega^2)^2 + (500\omega)^2]}}$$

The critical speed will be when

$$\omega = \sqrt{\frac{F}{M}} = \sqrt{\frac{10\,000}{100}} = 10 \text{ radians per second}$$
$$= 95 \text{ r.p.m.}$$

ω	Speed	d	ϕ	R	θ
rads./sec.	r.p.m.	ft.	deg. min.	ft.	degree
1	9·5	0·0001	2 52	0·0101	0·00005
5	47·5	0·0032	18 26	0·013	0·0004
7	67	0·0079	34 37	0·017	0·00102
9	86	0·0166	66 57	0·022	0·0023
10	95	0·02	90	0·022	0·0025
11	104	0·0205	110 53	0·019	0·0021
15	143	0·0155	149	0·009	0·0006
20	190	0·012	161 34	0·004	0·0002

These are plotted on Fig. 7, from which is drawn Fig. 8, which is a combination of Figs. 6 (a), (b), (c) and (d).

Fig. 6 will explain why, when balancing, say, a rotor by running it in spring-controlled bearings until it runs out and marking the place with chalk, the correct position for the balance weight is not opposite the chalk mark but is behind this position. The chalk mark will be at the end of the radius R, while the correct position for the balance weight is on a radius opposite to r.

A knowledge of the angle ϕ would certainly help to determine the correct position for the balance weight, and so save time over this operation.

One of the reasons why the expression first given fails to represent the behaviour of the centrifugal governor now becomes apparent. The forces Fd and $M\omega^2(d + r)$ are not mere scalar quantities but are revolving vectors. It is because the governor works in rigid guides, which prevent the various forces taking up their correct relative phase relationships, that it fails to show the peculiarities of a whirling shaft.

Another way in which the first expression was quite at fault was in assuming that if the original permanent set of the shaft was r and the bend due to the fact that the shaft was rotating was d, then the total bend of the shaft was $(d + r)$ and the restoring force $F(d + r)$. In actual fact d and r are seldom in the same direction and the restoring force may be anything from $F(d + r)$ to $F(d - r)$, and only in these two extremes (which occur at zero and infinite speeds respectively) does it pass through the centre of rotation.

In ordinary transverse vibration there exists an alternating strain in the material of the shaft which absorbs energy and fatigues the material. When two vibrations combine with a rotation to make a circular whirl, the strain no longer alternates but is fixed and constant for any particular speed, so that the air resistance is all there is to limit the amplitude of the whirl. This looks very small but it must be remembered that the disturbing force $M\omega^2 r$ is also generally very small.

It is, of course, very rarely safe to run for any length of time at the critical speed unless steps are taken to increase the friction by some means.

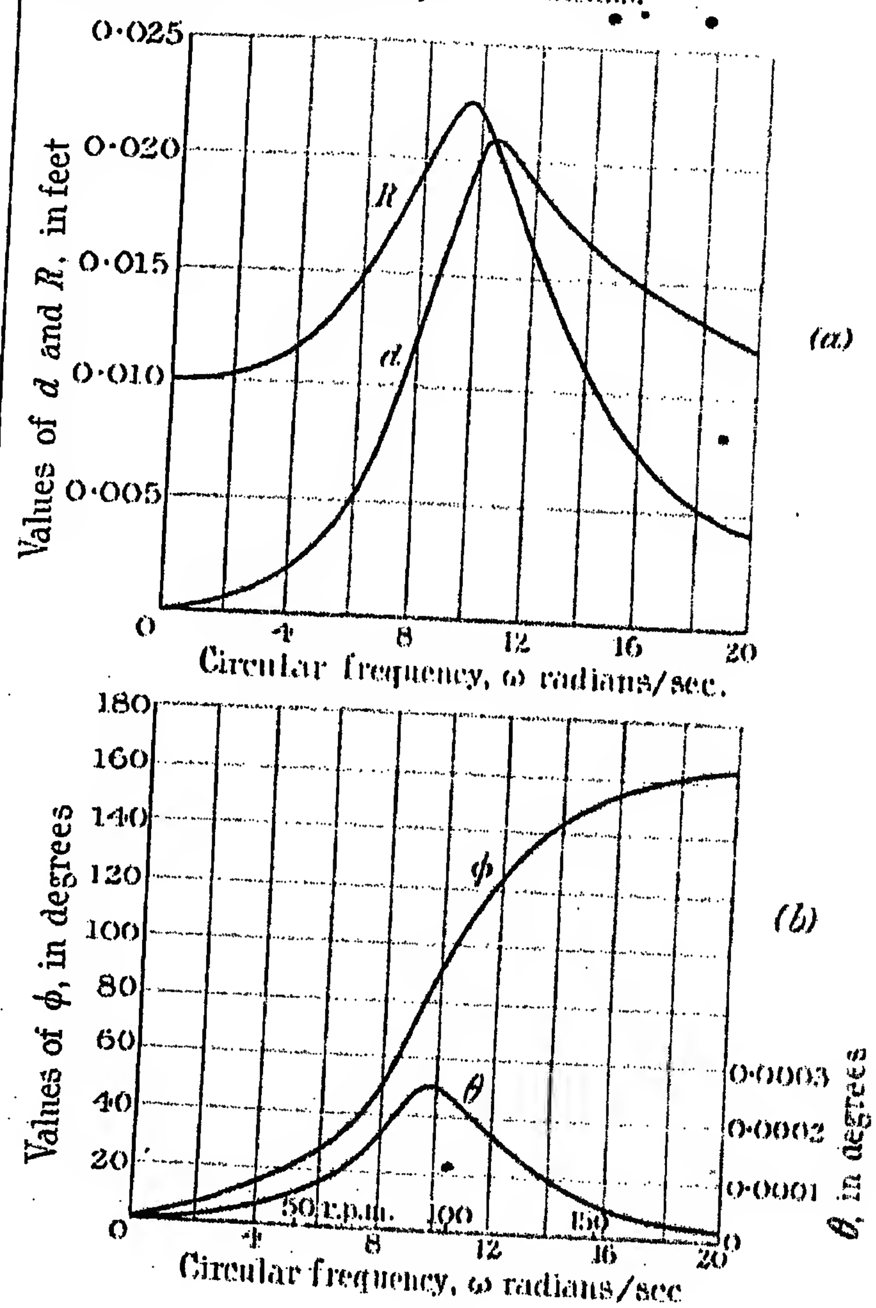

FIG. 7.

All the above remarks refer to a vertical shaft. The case of the horizontal shaft presents some additional interest; this shaft is deflected by the force of gravity by an amount equal to Mg/F.

At speeds under the critical, the shaft will not straighten itself but will continue to sag while revolving.

It is important to realize that although the shaft appears to keep the same form and to be stationary in space, it actually bends during each revolution. The material of the shaft is subjected to an alternation of strain, the only difference between this and the case

of simple vibration being that here the strain travels round the section instead of across a diameter.

In changing from a rectilinear vibration to a circular whirl, two of the fundamental properties of vibration become hidden. In a rectilinear vibration the material of the shaft suffers an alternation of strain from a maximum at the ends of the vibration to zero in the centre. In a similar way, the energy of the mass changes from all potential at the ends of the vibration to all kinetic when passing through the position of rest.

In adding two rectilinear vibrations at right angles to form a circular vibration the material of the shaft still suffers an alternation of strain, but the mass appears to lose its characteristic change in energy from potential to kinetic, and vice versa, it being now endowed with uniform circular motion.

On further adding a rotation, of a speed equal to the frequency of vibration, the shaft no longer suffers alternation of strain, each portion of it having a strain fixed in direction and amount.

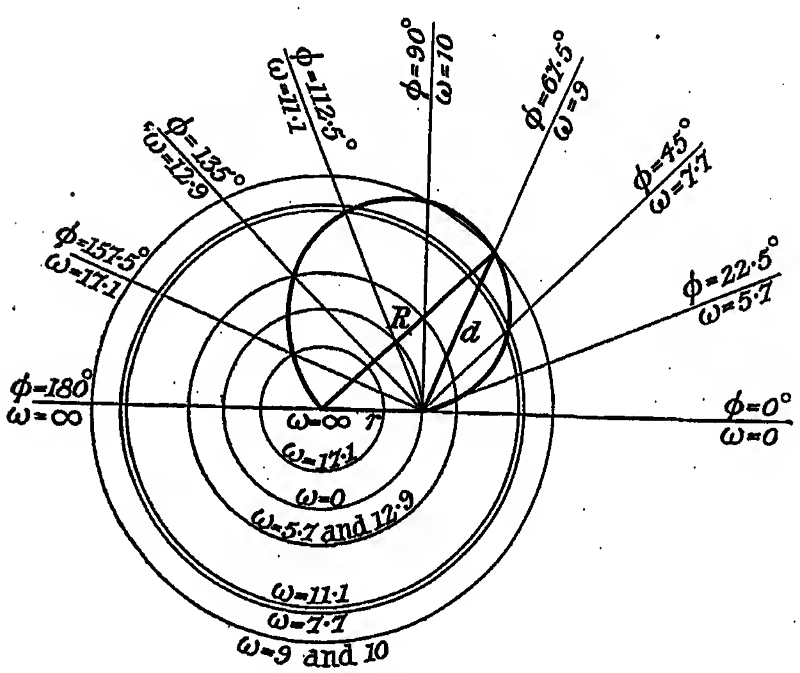

FIG. 8.

These two series of changes may seem to some minds to show that the motion is no longer a vibration; but there are other examples in nature of a body suffering a combination of several different motions at once, in which the combined motion, although undoubtedly the resultant of the various component motions, does not partake of the nature of any one of them, but, like the whirl of a shaft, is capable of being resolved again into each component with its recognizable peculiarity.

A conical pendulum is a good example of this. A mass revolving in a circular path at the end of a string is a pendulum obeying the laws of vibration and travelling round in its circle in the same time as it would travel across the corresponding diameter if it were endowed with only one of the two rectilinear vibrations. The projection of this circular motion on any two vertical planes would be identical with the motion of an ordinary pendulum of the same length. Yet the combined motion has neither of the two characteristic properties of ordinary vibration; there is no alternation of strain in the material and no change of energy of the mass from kinetic to potential.

Experimental Verification.

We have made the following experiments which can easily be repeated and which we think throw light on the subject of whirling.

The first is the classical experiment of a mass on a bent shaft. If run for any time at a speed in revolutions per second equal to its natural frequency in vibrations per second, it runs further and further out of truth until something breaks, but if hurried through this critical speed it runs truer at much higher speeds than at very low speeds.

Next we fixed two parallel guides stationary in space just far enough apart to allow free motion of the shaft. On repeating the above experiment all the motion was in the plane of the guides but otherwise obeyed the same law, i.e. the vibrations increased until the critical and then almost died away.

Next, the same guides were used but revolved with the shaft as in a centrifugal governor. The shaft then whirled further out until the critical speed but would not go back again and run true above this speed.

Next, the guides were removed and the flywheel mass was illuminated by a neon lamp through a contact maker on the shaft which switched on the lamp for about 1° of revolution. (The neon lamp will withstand double voltage under these conditions and will give more light.) A spot was painted on the flywheel and a pointer fixed in space so that the neon lamp was illuminated when these two were together at very low speeds. On increasing the speed the spot was seen to describe a circular path, as shown in Fig. 8. It was arranged that the flywheel should be illuminated at the instant when the initial eccentricity was opposite the pointer. If d and r were always in the same line, the spot would be seen, on increasing the speed, to move in this direction further from the centre, instead of which it moved round the circular path shown in Fig. 8, and at the critical speed the shaft was shown to be displaced at right angles to the original eccentricity. At high speeds the spot settled down in line with the pointer but nearer the axis of rotation.

Other Critical Speeds.

It has been suggested that a possible critical condition occurs when the shaft is rotating at 71 per cent of the true whirling speed. This has been based upon the idea that as the shaft is rotated its effective stiffness is reduced by the centrifugal force. We have seen that the true whirling speed is at an angular velocity $a = \sqrt{(F/M)}$, F being the true stiffness of the shaft. It is assumed that the effective stiffness of the shaft in rotation might be $(F - M\omega^2)$, and by analogy another critical speed might be expected at an angular velocity

$$\omega_1 = \sqrt{[(F - M\omega_1^2)/M]} = \sqrt{(a^2 - \omega_1^2)}$$

from which

$$\omega_1 = \frac{a}{\sqrt{2}} = 0 \cdot 71a$$

We have repeatedly run shafts at 0·71 of their true critical speed, with negative results, and it may definitely

be stated that no such additional critical speed exists. In the light of our previous remarks it is evident that the reason for this is that resonance can only occur if there is a disturbing force acting at right angles to the restoring force, and this is only the case at the speed for true whirling. At all other speeds, including that particularly under discussion, the line of action has a fixed and definite orientation to the disturbing force appropriate to the speed, and it is only at the true speed of whirling that this angle has a value of 90°, and consequently only at this speed that the conditions are critical.

All our work refers to a shaft with an initial eccentricity which provides the disturbing force (all real shafts being necessarily of this kind), and what happens in the case of a perfectly true shaft need not be discussed at length. A periodic disturbing force external to the rotating system and of the same circular frequency might be provided, in which case the shaft would remain perfectly stable at all speeds other than that corresponding to the natural frequency. Only when a speed corresponding to the natural frequency is reached would there be instability.

The case considered, of a mass placed centrally on a weightless shaft, is chosen for its simplicity in demonstrating the particular points raised. The more complicated happenings of whirling, e.g. second and other critical speeds, are, however, explainable with increased simplicity on the vibration theory. A shaft may whirl in as many ways as it can be set into transverse vibration.

If the masses are so placed, e.g. at the end of an overhung shaft, that their plane of rotation is affected by whirling, then gyrostatic forces will be called into play which may slightly modify the fundamental critical speeds and even introduce others entirely due to gyrostatic action. This has been investigated by Stodola (see Bibliography).

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TEES-SIDE SUB-CENTRE: CHAIRMAN'S ADDRESS

By C. O. Brettelle, Member.

(Abstract *of Address delivered at* Middlesbrough, *23rd November*, 1923.)

ELECTRICITY SUPPLY—SOME TENDENCIES.

The title given to this address implies a regard for the future and therefore for the past also, since it is necessary to study history if only in order to prevent history repeating itself. In 1882, the year of the first Electric Lighting Act, two theories were uppermost in men's minds, and with those theories new subjects for industrial legislation had to be squared. One was the kind of municipal socialism associated with Joseph Chamberlain's early career, and the other rested on a belief in the virtue of unrestricted competition and unfettered private enterprise. These not altogether compatible views were compromised in the Act referred to by jettisoning private enterprise; for the terms upon which it was permitted to function were such as to make it an adventure too speculative to win the investor, and too sure not to yield a golden harvest to excite the speculator. Thus the role of pioneer mainly devolved upon the municipalities, which was not only a reversal of the orthodox principle that the financial risks attaching to untried schemes should be left to individual effort, but it also deprived the industry of the greater latitude in experiment, so valuable in initial stages, more readily possible under private control. At the present time the total capital sunk in the supply industry is close on £200 000 000 (nearly double what it was in 1914) divided about equally between public and private interests. Of the 90 millions privately subscribed, 40 per cent is in the form of debentures, which appears to indicate that even now the inducements to capital are not any too good.

What our legislators overlooked was, on the one hand, that the needs of local government did not automatically delimit the area most suitable for the supply of electricity, and, on the other hand, that electricity from public mains has, and always will have, powerful competitors, since people want light, power and heat of the most efficient kind, irrespective of its form. Furthermore, the value of competition as a factor in keeping prices at a low level is dependent on the ratio of standing charges to running charges being low. In the business of supplying electricity this ratio has always been very high; as standing charges, rightly considered, include not only interest, depreciation and obsolescence in respect of generating plant and mains, but also all those operating costs that do not vary with output, such as by far the greater proportion of salaries and wages and even some part of the costs of overhaul and maintenance and of the fuel burned in banking boilers between peaks.

Nevertheless, it was deemed advisable to make competition compulsory by Act of Parliament, and so in London we find Orders for the same area granted to two companies which, until 1908, were forbidden to combine or enter into working arrangements, and were compelled to lay their cables in the same streets. Thus standing charges were duplicated and the additional cost necessarily handed on to the consumers. It was not until the year 1900 that a broader view was reflected in the passing of special Acts for the supply of energy for power purposes over wide areas. The incentive came from an awakening to the possibilities of extra-high-tension three-phase transmission. Technical and commercial considerations alike demanded that the supply of electricity should be regarded as something more than a struggle with the local gas undertaking, and an advance from the parochial to the regional outlook was made. Progress towards the present stage was hastened by the impressiveness of the work performed by electricity during the war; but the appointment of a directing and co-ordinating body such as the Commission would have become, sooner or later, as necessary to our welfare in peace as a general staff would be in war. This appointment, together with the Electrical Development Association jointly subsidized by undertakings for their common good, symbolizes the advance, as it were, from the heptarchy, an aggregate of isolated units, to the nation, built up of consciously related parts each enjoying a liberal measure of self-government. The coming of the Commissioners is perhaps 10 years overdue, but not much more, since in the earliest days of any movement a tendency towards semi-anarchy has its value in breeding a race of self-reliant men and in producing a welter of differing ideas and practices, from which a later centralization can select. Particularly in this country is diversity truly creative. It is sometimes termed "muddling through" and is as wasteful and as triumphant in its result as evolution itself, of which indeed it is but a healthy manifestation.

Another sign of the trend towards the larger outlook is seen in the machinery voluntarily set up for the discussion of matters of common interest among the three partners in industry, viz. capital, technical and administrative staffs, and manual workers. In the electricity supply industry the Whitley idea is perhaps more strongly entrenched than anywhere and should undoubtedly arouse esprit de corps among all who work within it, in addition to serving its more obvious purpose of encouraging conciliatory methods. The need to attract capital has been referred to, but brains

are requisite for its application. In order to attract good men remuneration must be adequate, and an improvement is to be noted in this respect from the days when it might truthfully be said that the income of an electrical engineer did not run to the consumption of his own product. Insistence on proper training and qualifications of entrants is a necessary concomitant. Recent apprenticeship schemes appear to have this in view rather than less desirable ends, while it is significant that this question of training is now being dealt with by the Whitley Boards and also that many public bodies require candidates for positions to hold some grade of membership of this Institution.

That the new times require more scientifically-trained men than did the old days will be patent to anyone comparing one of the older stations with a modern more or less standardized turbine station.

Then the most important instruments were on the switchboard, facilitating maintenance or restoration of supply, while only a CO_2 recorder (if that) gave some kind of a clue as to what was the efficiency of the stoking. The chief qualities of a good station engineer were initiative and resource in emergency, whereas to-day his counterpart is almost necessarily a fuel economist first of all, and the most carefully regarded instruments are (or should be) in the boiler house.

Technical education, however, has its limitations, and an engineer who is only an engineer is less than an engineer. It must be supplemented by a general education and a knowledge of the world that will enable him to profit by every enlargement of his experience. It has been well said that the ultimate test for the survival of Western civilization will be the ability of European nations to adapt moral and mental faculties to situations formed by progress in mechanics. Magnanimity and a sense of proportion are therefore particularly to be desired in electrical engineers whose part in material advancement is destined to be of ever increasing importance. Though there are many proofs that our profession is not deficient in these respects, it is obvious that a difficult and possibly a thankless task is in front of the Commissioners in reconciling the conflicting interests of divers undertakings and in compelling backward undertakings to be more progressive. It may be that on the North-East Coast we are apt to underrate the difficulties involved in co-operation between undertakings elsewhere, as we have here what has been aptly described as a "Joint Electricity Authority without its drawbacks," due to the fact that arrangements for mutual assistance are in force wherever practicable between municipalities, power companies and industries having waste heat for disposal. These arrangements are none the less happy for having come about as ordinary business transactions—the only efficient substitute for force or fraternity that our civilization has yet devised for dealing with its wants on a large scale. As regards systems of supply, the image of the future is reflected in the most advanced current practice. That is to say, the best of the existing three-phase alternating-current power stations will be linked together to supplement the output of new stations running at as near 100 per cent load factor as possible, and subject to the control of one load dispatcher for each group. The capacity of these new stations will be as large as permitted by the sites available, having due regard to water supply and railway sidings, but will probably not greatly exceed 200 000 kW under one roof. Auxiliary plant, it goes without saying, will be driven by alternating-current motors. Thermal efficiencies will probably be at least 30 per cent better than the highest (17·8 per cent) hitherto obtained, or in other words 1 kWh will be generated from little more than $1\frac{1}{4}$ lb. of fuel, which is under half of last year's average for all public generating stations; though whether the last 1 per cent or so of such efficiency will justify the cost of obtaining it has to be proved.

Coal, by means of which all but 5 per cent of $5\frac{1}{2}$ thousand million units were generated last year for public supply, will doubtless continue to be the main source of our energy. The tendency will be to raise steam pressures considerably, and the 475 lb. per sq. in. at one power station in this neighbourhood is probably only the precursor of still greater advances on older practice. The gas turbine, however, is an interesting possibility of the future. One of 10 000 kW is said to be running on oil-gas in Germany with an overall thermal efficiency of 28 per cent, which is, nevertheless, probably not sufficiently in advance of reasonably anticipated steam performance to affect the situation to any marked degree, taking into account all relevant factors.

Water power, with its superficial prospect of getting something for nothing, has its fascinations for many people, but the amount of coal to be saved by this means is not likely to be appreciable. Instances of its successful exploitation are few, and those on only a small scale, the aggregate output now being but 32 million units per annum, or about one-half of 1 per cent of the total generated by all methods. It is estimated that in Scotland, where the potentialities are greater than in England, about 140 000 kW is available from this source, but the average capital cost for power station construction alone has been given at a figure at least twice as much as that for a large steam station. To transmit this power to the big industrial centres would necessitate, on an average, the running of 80 miles of transmission line over very rough country; consequently it is not easy to see how the actual cost of current to the consumer can compare favourably with that supplied from a station like the one at Dalmarnock. Probably the solution will be the erection at the cascades of works having a load factor approaching 100 per cent, as, for instance, has already been done in the case of the aluminium works in North Wales and near Ben Nevis, when capital charges, not inflated by expenditure on transmission lines, being spread over a large number of units are relatively of less importance. In similar manner illusory hopes are sometimes aroused by "waste heat," from which last year the quite respectable amount of 184 million units were produced, or about $3\frac{1}{4}$ per cent of the total; but the capital charges per unit are high owing to the comparatively small size of the power stations and the need to provide adequate independent standby. This source, moreover, will

tend to dry up due to more efficient plant reducing the amount of waste heat for disposal and due to its intensive use in the works themselves, either as raw heat or else for the generation of electricity for major operations such as smelting, rolling and winding, so that the other requirements of the works must be supplemented by current from the public mains.

Although it would seem that coal is destined to continue to occupy the premier place as fuel in the production of electricity, it does not follow that combustion will always be carried out in the same wasteful manner as it is to-day. A far-reaching development would be the generation of steam for producing electricity as a by-product of the slow destruction of coal for its valuable constituents. So far very little has been attempted in this direction, but it would appear to offer scope for the dangerous game of prophecy.

Turning to the question of transmission, the three-phase system will, it is safe to assume, hold its own at pressures in excess of those now in common use in this country, and 60 000 to 70 000 volts is likely to be common practice in the early future.

It is not suggested that what are sometimes termed "super-power stations" with extra-high-tension transmission will meet the demand for electricity everywhere. The medium-sized station situated at an appreciable distance from a transmission system and efficient for local requirements will no doubt continue its individual existence as long as its operating costs are low enough to make interconnection commercially unsound.

There still remain the problems of supply to the small town, the village and the isolated farm. The needs of the first can in most cases be met, until a bulk supply becomes available, by oil engines and suction producer-gas engines. Supply to a village or township presents greater difficulties. The tendency seems to be for such undertakings to be established without statutory powers, as the £300 or so necessary to acquire Parliamentary sanction would be a heavy item in the capital expenditure. Thus of the 30 consents given by the Electricity Commissioners during the past year for the erection of new generating stations, no less than 18 were for non-statutory undertakings. Seldom could the financial prospects be made attractive unless the cost of generating plant and attendance were eliminated to some extent by taking energy in bulk from a transmission system. Failing that, current might be obtained from the plant of a local industry or water wheel, or else from a small petrol or paraffin set at a garage or on the premises of a hardware merchant willing to risk financial loss from the sale of current in return for the exiguous profit to be derived from wiring houses and selling fittings. A further alternative would be co-operation with the local gas undertaking (if any) so that administrative and operating expenses could be shared. In any case it is very important that these plants should be designed to be semi-automatic and self-regulating, as constant attendance would be out of the question, in view of the expense. Supply would be available only from dusk to dawn in many instances, and reliability must be deemed to be of quite secondary importance. Over-insurance in this respect, always to be guarded against, would prove an insuperable handicap to a small concern.

The cost of tapping a transmission line, without sacrificing its security, to meet a demand of a few kilowatts is often almost prohibitive, and, *a fortiori*, to supply individual farms is generally entirely so. There is here a very important field for investigation, since it is imperative that agriculture should receive whatever stimulus may be possible. Apart from the necessity of a modicum of home-grown food in case of national emergency, it is essential that we, as an industrial country, should continue to recuperate our urban stock from men reared in more natural surroundings.

While referring to distributing systems it would be as well to touch upon the question of their administration. It is on the whole desirable that this side of the business, which does not so noticeably lend itself to centralized control, should remain in its present hands, whether municipal or company. It is, nevertheless, urgent that steps should be taken to secure a greater measure of uniformity in low-tension pressures. As things are, apparatus in use in one town may be unsuitable elsewhere, and this must add appreciably to its cost.

If electricity is to be generated and transmitted as three-phase alternating current there is a clear gain in distributing it on this or, in the case of residential or shopping centres, on the single-phase system. Any special advantages of direct current are in all but a few cases offset by the cost of, and losses in, transformation, and by the heavier outlay on the maintenance of mains. It is, furthermore, without the flexibility of alternating current to cope with overloading in congested districts and with the growth of suburbs.

General rules are nevertheless no substitute for intelligence in dealing with special instances. Thus we have the case of the industrial quarter of a town where many direct-current motors have been installed, the cost of replacing which would more than balance the capitalized savings accruing from a change-over to alternating current. In this connection it should be borne in mind that constant attendance at converting substations is likely to be greatly reduced in the near future, as automatic systems and rectifiers come into more general use. No one need be sorry for this change; for attendance at a substation, though useful as a method of gaining experience, becomes after a very short time of service an occupation fit only for a Robot.

The case of the battery vehicle, which is assured of a brilliant future, can be met by the provision of small rectifier stations, just as the requirements of the present-day motorist are met by the kerb-side petrol pump.

There are, in addition, many special industrial processes requiring direct current, but its chief enclave will undoubtedly be found in railway traction.

One feels almost sorry to be compelled to agree with the findings of the Kennedy Committee of 1920 in this respect, but the weight of technical evidence submitted was overwhelmingly in favour of committing

us to a far-reaching high-tension direct-current scheme.

Electrification of the main lines will undoubtedly have an important bearing on the transmission schemes of the future, and it is greatly to be hoped that the railway companies will now tackle this problem in earnest. One cannot but suppose that the North-Eastern Railway, if its past record is any criterion, would have already made more headway in this direction but for the necessity of waiting for other districts to come into line. Sir Vincent Raven's datum line of 2 lb. of coal per unit will without doubt be common power-station practice before the railways are ready. The electrification of suburban traffic, where quick acceleration is of greatest importance, has long passed beyond debate, and mineral transport has been tried within a few miles of this hall. Standby losses that have so much weight in the latter case are of greater moment than is generally realized in express train service, while the flattening out of maximum speeds may be expected to reduce maintenance costs.

Main-line traction, though representing a potential demand for electrical energy on a colossal scale—no estimate of the extent appears to be available—is only one of the directions in which immense developments may be expected. Heating in all its forms presents an almost limitless field. The possibilities of the situation may be sensed from what is already a fact in the United States. At Pittsburg we find no less than 335 000 kW of industrial heating load, of which roughly two-thirds are accounted for by the iron and steel works, leaving no less than 110 000 kW for various industrial uses.

So far the scope of domestic heating (which includes cooking) has been restricted to fairly well-to-do people and to somewhat specialized housing schemes. It is in this respect that electricity now meets with the keenest competition, especially in providing economically enough hot water to fulfil civilized needs. General acceptance of its superiority to other heating agents calls for the education of the public along lines familiar to those of us who remember the debates of some 20 years ago as to whether electricity was even as good an illuminant as gas, and when it was generally assumed to be necessarily much more expensive. It is true that electric lamps have been considerably improved since those days, but also it is clear that in the design of cooking and heating apparatus finality is a good way ahead of us. That the public is now in a mood to respond to culture is shown by the fact that last year the consumption of electricity in this country was greater than at any previous period—greater than during the war or the post-war boom. This increase is attributed mainly to domestic uses, which, unaffected to the same degree as industrial supplies by trade depression, have justified the expectation of their stabilizing effect on output.

The goal of the supply industry is to fulfil a public service and not merely to indicate with what efficiency we can generate electricity, however important a bearing the latter may have on the position, and the credit of low works costs is a barren one unless we can at the same time awaken a demand for the product. The old saying that "demand creates supply" is true only up to the point of normal saturation. If that point is to be passed—and judged by modern standards it is reached at so early a stage that a commercial system dependent upon it would be primitive in the extreme—the supply must create the demand.

The utilitarian philosophy, which left its mark on the methods of the last century, failed to take into account, among other things, that lack of introspective faculty is common and that inertia is the ruling passion of mankind. Man does not intuitively know what he wants, save as he is directed by a few primitive impulses, and he is usually disinclined to make much effort to discover his needs beyond the satisfaction of such impulses, ambition included. The fruits of the increasingly large sums spent during the last decade in advertising furnish an indication of how supply creates the demand; and we have a more pointed illustration in the forward policy of some gas undertakings which let out cookers and fires either free or at a nominal rent in order to excite a demand for their gas. The result is an effective demand many hundreds per cent in excess of the unexcited demand. In addition to the demand thus directly created there is a further stimulant in the suggestion of the ability of the familiar agent—electricity, gas or whatever it may be—to fulfil various requirements. It will be evident that the development of electrical heating to an appreciable degree depends upon the cost and reliability of the apparatus, and this implies its hire, supervision and maintenance by the supply authority. A supply authority would do well to confine its attention in this respect to such apparatus as really fulfils a daily need and which consumes an appreciable amount of energy. Other articles will, with the help of a suitable tariff and educative propaganda, find their way into common use as a matter of course.

One method of compassing this excitation would be to set aside a portion of any financial surplus to form the basis of what might be called a profit-sharing scheme with the consumers. Each of the latter would be presented on payment of his account with a voucher proportional in value to the amount paid for current in the preceding 12 months. These vouchers could be exchanged for, or given in part payment of, scheduled current-consuming apparatus at the showrooms of contractors or of the undertaking itself, in which the cashier's office should be located. Presumably the next year there would be an increase in consumption of current and therefore in the profits and also, with snowball effect, in the kilowatts of the apparatus given to the consumers as their share in this co-operative enterprise, and so on.

The framing of a suitable tariff plays a very important part in the process of stimulation. The most successful domestic tariffs include a high fixed charge (whether based on the number of lampholders installed, rateable value, floor space, or so many units at a high figure, etc.) and a low running charge. The ideal to be aimed at is to reduce the latter to negligible proportions, thus at the same time meeting the standing charges of the supply authority and enabling the consumer to anticipate within a small margin what his

liabilities will be. The *arrière-pensée* is of course that the consumer will use current more freely. A choice of tariffs at the present stage, when new habits of thought have to be inculcated and psychology has therefore to be taken into account, can well be offered to prospective consumers who press for it. It is no longer incumbent on an undertaking to charge on a flat rate of so much per unit; but it will probably be expedient to continue to do so rather than lose business, if only for the sake of the consumer who desires simplicity above everything, provided the flat rate be made less favourable than those constructed on a more scientific basis. This proviso is quite legitimate, since the consumer chooses the flat rate either out of idiosyncrasy or else because he finds it enables him to evade his share of the standing charges.

So much for domestic tariffs designed mainly to foster the heating load with its desirable possibility of a Sunday peak. The industrial load naturally requires a different method of approach. There is in the first place the greater amount of current consumed. There is also the greater diversity of conditions, as well as the necessity for a direct reference to economic values, which are not always the chief care of the same individual consumer *qua* domestic man.

A rough approximation towards covering standing charges such as may be allowed in a domestic tariff would be unsuitable for industry, though the same general principle should be adopted (as in the case of water power supplies) of a fixed charge as high as possible and a running charge as low as possible. The importance of standing charges cannot be too much stressed. To take an example from figures recently cited in the technical Press in connection with a modern medium-sized generating station. It was found that to increase the load factor from 20 per cent to 40 per cent decreased the fuel cost per unit by only 5 per cent, and that the total cost of repairs, maintenance, oil, water and stores increased in proportion to the output. For the same variation in load factor, the capital charges and salaries and wages per unit were halved. Thus running charges drop from, say, 0·41d. to 0·398d. per unit, whereas standing charges drop from 0·614d. to 0·307d. per unit. Carry this calculation to 100 per cent load factor and we find running charges 0·386d., as compared with only 0·204d. standing charges. These standing charges refer to the generating station only. If they be doubled it will show nearly enough for our purpose the effect of standing charges on the position of the undertaking as a whole. In designing a tariff, running charges can conveniently be considered to be constant within limits for a given price of coal, but the standing charges have to be adjusted over a wide range if they are to be equitable. The maximum-demand system usually meets the case between consumers of the same class, but not necessarily between those of different classes. For instance, the maximum load of one consumer may coincide with the peak load of the station, whereas that of another may be made at a more convenient hour of the day or night or during the week-end, thus adding very little to the standing charges of the undertaking. Care must be taken to avoid incorrectly allocating standing charges so as to depreciate the competitive value of electricity.

In practice it is not, of course, always possible to carry fully into effect these principles, which are based, as most principles are, upon a static conception of things. In reality conditions are for ever changing, so that a reasonable estimate of net results has to be made for some time ahead, and some compromise is necessary. The consumption and demand at every works fluctuate from month to month; strikes, lock-outs and foreign complications occur; or the undertaking develops, necessitating the installation of new plant and mains, more or less costly than the old.

The flat rate usually quoted for current taken in relatively small quantities is more defensible for motive power than for lighting. If a two-part tariff were imposed upon each consumer operating one or two motors intermittently, the resultant average rate per unit would frequently be prohibitive. It would also be inequitable, as the diversity of the incidence of the demand on the power station makes it probable that the standing charges would be considerably more than covered. It will be obvious, however, that a flat rate is a compromise and must in many cases involve the undertaking in a loss.

It has been said that commercial supremacy in days to come will fall to the nation having the most efficiently exploited resources for the generation of electricity in abundance. Let us for the moment imagine ourselves living in the omnipotent and omniscient State of the Utopians. We will assume that the State has made a special feature of electricity supply. The rulers would desire to foster various industries, some for the wealth they would bring to the country, others for advantages of a social kind. There would be no better instrument to their hand for compassing their ends than electricity; for electricity provides the almost ideal flexible coupling between the prime mover of the most efficient kind and the smallest machine, and presents an extreme illustration of the economic paradox that the displacement of the labour of hundreds of men may provide work for thousands. It furnishes the only practicable means of de-concentrating industry, and is the sole hope of any revival of cottage craftsmanship. It brings the only prospect of dissipating the pillar of cloud by day and by night over our cities and makes possible cleanliness without drudgery in the home. It also gives an enlargement of intellectual and material resources by its instrumentality in promoting rapid and economical transport. In short, electricity presents the best material framework on which to base the old democratic formula of "the greatest happiness of the greatest number." We know, of course, that such a State and such rulers never will exist, and that any less perfect substitute would not fulfil our purpose as well as we can with reasonable luck and courage accomplish it ourselves. But Utopias have their uses. They present to our view some kind of a mirage towards which to blaze out our path, knowing that we must depend on our own efforts, yet willing to co-operate with all who have a similar goal, rubbing off our angles in the give-and-take of things, and, it may be, gaining a few bruises in their stead.

NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

By G. A. JUHLIN, Member.

(ABSTRACT *of Address delivered at* MANCHESTER, *6th November*, 1923.)

The electrical industry, in common with other great industries, is at present passing through difficult times, and no one can predict what the future has in store. It is at such times as these that the moral fibre of those engaged in the industry is tested to its utmost.

I think it is well that we should realize that our Institution has a great responsibility, and that it behoves everyone to pull his full weight in order to make a speedy recovery possible. How this weight is to be applied must of necessity be determined by each member himself, but I suggest that one way is to attend our meetings and to give his knowledge freely. It is also incumbent upon those responsible for the governing of the Institution to give every facility to all members to contribute papers and to enter into the discussions.

I am not sure that at present we are working on the best lines to obtain the results that we wish to obtain, which I take to be the lifting of our industry to the highest possible eminence throughout the world. To attain this position it is necessary to encourage every branch of the industry to give its quota of knowledge; but I am afraid that our present system is not conducive to this condition. There seems to me to be a tendency to set a standard which deters members from presenting papers, because they feel that the subject with which they are able to deal is too mundane to present in the form of a paper, or that it is not sufficiently technical to be accepted.

In order to obtain the best results from an industry it is essential that the user and the maker of the plant should be in close contact. It would therefore appear desirable to encourage papers from operating engineers. In using this expression I am including not only those engaged in the generation of power but also power users. Electricity is constantly being introduced as a motive power into new fields, each having special requirements which must be given consideration in the construction or the general lay-out of the plant.

Consider, for example, colliery installations with their many special requirements. This is, of course, a field where electrical energy has been in use for many years, and yet comparatively few papers on the subject have come before this Institution. There is, undoubtedly, need for co-operation between this Institution and the engineers responsible for electrical installations in our collieries. It seems a great pity that a separate organization should cater for the mining electrical engineers, and it would certainly indicate that some effort should be made to obtain co-operation.

Marine work bristles with special requirements, and is a comparatively new field as far as electricity is concerned. In other directions also there seems to be room for expansion.

Speaking from the point of view of manufacturing, there seems to be need for more papers in connection with actual workshop problems. This side of our industry is not strongly represented in the Institution, and I am convinced that this fact is retarding our progress very considerably.

It is not possible to obtain satisfactory results without considering all factors that make the whole. Manufacturing methods are so closely related to designing that they can hardly be separated if progress is to be made. While designers interchange views through the medium of our meetings, there is a great deal of reticence regarding shop matters. This is very apparent when comparing the conditions in this respect in the United States with those in this country.

I am firmly of the opinion that a great deal could be done by encouraging the members to present papers dealing with manufacturing problems and shop organization. It would certainly bring out the fact that the manufacturing side offers a promising field for the technically trained engineer, which field does not seem to be fully appreciated at present.

The statement that we can solve our industrial problem only by increasing output has been made so often that it is becoming hackneyed. I do not think it is appreciated, however, that this cannot be obtained by the efforts of the workmen alone. It can only be done by careful organization and elimination of useless effort, and this surely is the work of the engineer, whether he be engaged in designing or manufacturing. I believe that it is because this fact has been recognized in the United States that they have progressed so fast.

There are of course many other factors, which cannot be dealt with here, conducive to the rapid strides of electrical engineering in America. There is one factor, however, which is very prominent. The question of utility is the keynote of all work. Super-excellence is not looked for or considered to be worth paying for. I was impressed by the remarks of an American operating engineer looking at a switchboard over here, to the effect that there was an unnecessary amount of nickel-plating on the instruments and the board generally. He said: "In our country we consider it bad, because it is apt to distract the attention of the operator due to the reflection of the lighting. We believe that the dials should be the most prominent thing on the board." It is difficult to decide how far to go in regard to the general question of appearance, for there is undoubtedly a psychological effect produced in giving the man responsible for looking after the plant something in which he will take pride, but I suggest that the mean lies somewhere between the practice of this country and that of America.

In comparing electrical development in this country

with the progress in America, it is necessary to consider the conditions affecting these developments. Natural resources in the form of water power have been potent factors in developing the electrical industry in America, coupled with the fact that very few towns had a gas supply at the time electricity was introduced. In this country, on the other hand, electricity has had to compete with a highly developed gas industry, which naturally retarded its progress.

One must also bear in mind that labour conditions have a great influence on the amount of power used in industry generally, and countries where labour is scarce have been forced to adopt means to reduce hand labour to the greatest possible extent.

While the progress in respect of the quantity of electrical plant in this country is behind that of other countries the quality is, in my opinion, second to none. I think that this is reflected in the excellent results as regards continuity of supply from our generating stations.

Generating Plant.

With regard to the size of units, British manufacturers are in a position to meet the demands in this respect. Sets capable of developing 40 000 kVA at 1 500 r.p.m., and 18 750 kVA at 3 000 r.p.m., are in commercial operation, and 25 000-kVA units at 3 000 r.p.m. are under construction. Ten years ago the largest unit at 3 000 r.p.m. was of 3 750 kVA rating, so that the development in the size has been truly remarkable.

The total electrical breakdowns of turbo generating plant manufactured, reported by two of the large companies, showed that in 1921 the total breakdowns experienced on their plant represented less than 1 per cent. Recent figures show that this figure is decreasing, which is a splendid result if we consider that pioneer work is being undertaken all the time.

Regarding the size of individual units, it should be stated that much larger units have been built both in the United States and in Germany than in Great Britain, except at 3 000 r.p.m. There seems to be a tendency to regard the size of the units built as a measure of the manufacturing capabilities of the country, whereas it is really only an indication that there is a demand for such large units.

A recent report on the operation of the 60 000-kVA sets installed in Germany during the war leads one to doubt whether these large units are justified. Should the demand for such large units arise in this country, however, there is no doubt that it would be met.

I have not been able to obtain any definite figures of the output of turbo generating plant in the United States, but I believe it to be approximately 2 million kVA per annum. In addition a large amount of hydro-electric plant is installed. Comparatively little hydro-electric work has been done in this country owing to lack of demand. Since the Armistice, however, considerable progress has been made in this class of work, orders having been received from the Dominions for generating plant, high-tension transformers, and switchgear.

The following table shows the total capacity of turbo-generator plant ordered in each year since 1912:

Year	Total kW	Year	Total kW
1912	162 000	1918	344 000
1913	271 000	1919	500 000
1914	269 000	1920	736 000
1915	333 000	1921	146 000
1916	344 000	1922	339 000
1917	562 000	1923	405 000

I think that this may be regarded as a very satisfactory rate of increase, and it is of interest to note that there has been a distinct upward tendency during the last two years. The small output for 1921 is, of course, due to the trade depression.

Transformers.

Since the Armistice, rapid strides have been made in transformer design and construction in this country. Considerable progress has been made, both in the size of unit and in the maximum voltage, to meet the requirements of the large power stations now being erected and also the requirements of the Colonial markets, where extra-high-tension transmission is being rapidly extended.

The largest transformers which have so far been built in this country are the 19 500-kVA three-phase 50-cycle transformers for the Barton power station of the Manchester Corporation, and the 7 800-kVA single-phase 25-cycle transformers for the Dalmarnock power station of the Glasgow Corporation. The latter size corresponds to 15 000 kVA at 50 cycles. Both these sets of transformers are of the oil-immersed forced-cooled type with oil circulation through external coolers provided with water cooling.

One of the principal problems in these very large units for super-stations is the question of transport and handling on site, which considerations govern the limiting size of units. The 19 500-kVA Barton transformers were actually built and shipped to the site with the transformers in the tanks and complete with oil, the total weight being 60 tons.

In high-tension transformer work it is satisfactory to note that British manufacturers have already obtained orders and delivered to the Dominions transformers for pressures up to 110 000 volts, and it can be confidently asserted that British transformer makers are now in a position to build satisfactory transformers for the requirements of any part of the world, and can successfully meet foreign competition.

Another interesting development, so far as tranformer practice in this country is concerned, is the growing use of outdoor transformers. These have, of course, been in use for many years in America, where conditions differ from those in this country.

It was not until building costs became so high during the war period that the question of outdoor substations was seriously considered in this country. Such transformer substations are now in operation in England, in many instances for 22 000 and 33 000 volts, and in one case for 66 000 volts.

The majority of these transformers are connected to extra-high-tension underground cables, which are led into the transformer through ironclad cable-sealing bells or trifurcating boxes of weatherproof construction.

In agricultural districts where a power supply is being

opened up there is also a tendency to place small distribution transformers out of doors, either mounted on poles or on concrete platforms.

In extra-high-tension transformers for cable testing, three-phase sets up to 300 000 volts have recently been built in this country, and single-phase units for insulator testing up to 500 000 volts.

Switchgear.

The increase in output from generating stations has necessitated development as regards breaking capacity of oil switches, in order to ensure satisfactory clearing of faults on the system. Armour-clad designs have been adopted for systems up to 35 000 volts, individual breakers having a rupturing capacity of $1\frac{1}{2}$ million kVA. All connectors are insulated and embedded in compound, which results in a very compact design.

American practice has developed in a different direction, the phases being completely segregated from each other.

Outdoor switchgear has been developed to correspond to the transformer development.

The first station of this type to go into service was that at High-street, Manchester. Similar gear is being installed at other places. The use of pole-mounted switchgear is also increasing, several schemes being in progress.

Considerable advance has been made in the detail design of the switches, and all this has increased the reliability in operation. Extensive tests have been undertaken in this country and in the United States. The fact that information of this kind is interchanged between the two countries is of immense value and has the effect of facilitating progress.

Industrial Plant.

The greatest progress has undoubtedly been made in our steel-works. Rolling mills have been electrified extensively and it is satisfactory to find that in 1921 there were more than 600 electrically driven rolling mills in this country, the largest of these having a maximum rating of 21 000 horse-power. About 300 of these mill motors have a normal rating of 300 h.p. or above. An interesting application of electrical driving is that of a tyre mill, a number of which have been installed. Owing to the changing ratio of inside to outside diameter of the billet in roughing, the speed of the rolls must have a variable ratio. This is obtained in a simple way by providing a separate motor for each roll and connecting them in series. Excellent results both as regards quality and output have been obtained from these mills. That the electrical drive is recognized as being superior to the steam drive is shown by the fact that practically all large reversing mills installed in recent years have been electrically driven and have proved an unqualified success.

It may be of interest to state that in 1921 the number of electrically driven rolling mills of 300 h.p. and above in the United States was more than 700, totalling over a million horse-power. A recent statement gives the total horse-power of electric motors employed in the steel industry of that country as 5 millions, and the total electrical energy absorbed as 8 million units per annum. It is difficult to visualize such stupendous figures, which are an excellent testimony to the successful use of electricity.

Mining Work.

Owing to the depressed state of the coal industry, comparatively small progress has been made as regards the installation in collieries of electrical plant, excepting winders. The need for increased output from the pits has brought the electrical winder into its own, and a considerable number of these have been installed in recent years, both for alternating and for direct current.

An interesting development in connection with winders is that known as the "S.P." scheme. Briefly this consists of a turbine driving direct-current generators through gearing, with a flywheel mounted on the shaft of the generators. By a special governor the speed of the turbine is reduced when a peak occurs, thus allowing the flywheel to give out its stored energy. In connection with the flywheel used in conjunction with the Ilgner sets, considerable progress has been made in design. By adopting special high-grade materials which permit of high peripheral speeds, it is possible to obtain 3·25 h.p.-seconds of stored energy per lb. weight of the wheel. This figure shows a high degree of efficiency in the utilization of material.

Marine Work.

The use of electricity on board ship is increasing very rapidly. So far it has not been employed to any extent for propelling machinery for British ships. An interesting example of the use of electricity for auxiliary machinery for marine work is that of an oil tanker. Thirty ships have been equipped with electrically operated auxiliaries.

Traction.

Considerable progress has been made in connection with the electrification of railways within the Empire. Although no main-line electrification has been undertaken in Great Britain, some of the Dominions have taken the lead in this respect. In South Africa direct current at 3 000 volts has been adopted, and for some of the Indian Railways at 1 500 volts.

Recent Developments in the U.S.A. and Canada.

This year has been remarkable as regards the demand for electrical plant in the United States. Turbo-generators of 62 500 kVA capacity in one machine are under construction. The speed of these units is 1 200 r.p.m., the frequency being 60 cycles. The weight of the rotor of one of these machines is over 100 tons.

Water-wheel generators having an output of 45 000 kVA have been in successful operation for about two years in the Queenston power house of the Ontario Power Commission. Five such units are at present in work, and five additional sets each having a capacity of 55 000 kVA are under construction.

Still larger units are under construction for the Niagara Falls Power Company, which is situated on the American side of the Falls. Two sets each having an output of 65 000 kW will be installed. The rotor of one of these generators is built up of 10 rings, side by side, each

weighing 40 000 lb., the diameter being 23 feet. The total weight of each machine is over 700 tons. Some generators built in 1903 for this Company had a capacity of 3 750 kW, so that in 20 years the size of individual units has increased 17 times—a truly remarkable development.

The question of "linking-up" is receiving a great deal of consideration, and as an example of what is being done in this connection may be mentioned that a frequency-changer of 35 000 kVA capacity is being installed for the purpose of interconnecting the 25- and 60-cycle systems of the New York Edison Company.

Other units of 15 000 kVA to 20 000 kVA capacity are under construction for various power companies. Synchronous condensers for transmission-line regulation having a capacity of 35 000 kVA have been installed, as well as many smaller units.

A notable advance in high-tension transmission work was the putting into commercial service of the 220 000-volt system of the Southern California Edison, and the South Pacific Gas and Electric Company. This is the highest voltage yet adopted for commercial work. Some indication of the size of oil switches may be gathered from the following figures:—

Weight of switch with oil	45 tons
Oil required	2 000 gallons per pole
Height to top of terminal	17 ft. 6 in.
Size of tanks	8 ft. × 5 ft. × 8 in.

Railway electrification is being undertaken on a large scale. The Virginia Railroad recently placed an order for the electrification of a part of their system, as it was found impossible to handle the mineral traffic with steam locomotives.

One of the most remarkable developments in America is what is known as the "Supervisory Control" system. Two methods of achieving control have been developed. The first is a system of relays and signalling devices, which link up all the stations to be controlled. This is termed "Audible Supervision," and is mainly adopted for hydro-electric generating plants and small sub-stations. The general scheme is that the supervisor can at any time put himself into telephonic communication with any station under his control by means of a specially developed keyboard and automatic dial.

If he desires to ascertain the conditions of operation in, say, No. 4 station he simply presses No. 4 key and the telephone dial connects him to No. 4 station. By means of audible signals he can ascertain the head of water, gate opening, etc. These signals are repeated automatically until another dialling operation is made by the supervisor.

"Trouble" alarm-circuits may be used to warn the supervisor that something has happened. This may be the operation of an overload trip on a circuit breaker, or any other operation that can close a relay. The warning is obtained by sending a high-frequency current over the line received by a loud-speaker in the supervisor's office.

The second system is that of "Visual Control." This has been developed for large systems with a number of large substations. Briefly the operation of this system is as follows:

For each operation in the substation there is a definite numerical code. The signal is transmitted by telephone keys which operate relays, and these in turn operate an automatic selector switch. Through this the code is transmitted to the station and decoded by a similar selector switch which operates the required relays performing any desired operation, such as closing a circuit breaker. Having performed the operation, the relays signal back to the supervisor the fact that the required operation has been performed. Small lamps are used for this purpose, hence the "Visual Control." The lamps are covered by coloured buttons, a red one indicating a closed circuit and a white one an open circuit. The relays and selector switches are those used for standard automatic telephone work, which have been in use for years, so that the system does not depend on new and therefore experimental plant.

One of the most interesting and, from an operative point of view, most important points is that incorrect operation is almost impossible, because the whole operation is reported back from the substation to the supervisor. The receiving circuit used in connection with the sender in the supervisor's office, and the automatic sender in the substation, will not under any condition respond to any incomplete or distorted code.

The tramway company in Cleveland (Ohio) operates four automatic substations, which are also controlled by a supervisor located in the offices of the company. The supervisor has full control of all the plant through two pairs of telephone wires, which are part of the telephone company's network. Exhaustive tests were made before the system was adopted, in order to determine whether the arrangement would cause any disturbance in the normal operation of the telephone system, but it was found to be entirely satisfactory. Operation has been highly successful and four more substations are being equipped with this control system.

Through the kindness of the chief engineer of the tramway company, I was able to see a rotary converter transferred from one section of the system to another, and it was certainly an object lesson on the efficiency of the system. I was told that since the supervisory control had been installed they had had less difficulty in operating the plant when disturbances occurred on the system than before the control was adopted. This was attributed to the fact that the operator is detached and therefore not influenced by the disturbance, and also that mistakes cannot be made in the operation.

About 40 equipments to control from 1 to 16 substations are installed or under construction. A number of these are for the audible system for water-wheel stations.

In conclusion I would say that while we in this country are in many respects behind other countries in electrical developments, the leeway is gradually being reduced.

I have already referred to the question of quality and I feel convinced that, given a fair field, the electrical industry, whether in actual manufacturing or in the generation of power, will meet any demands for power that may be put upon it. I am also sure of this, that if we in this Institution do our part, as I have no doubt will be the case, there is every reason to look forward to an increased prestige of our industry.

PROCEEDINGS OF THE INSTITUTION.

702ND ORDINARY MEETING, 18 OCTOBER, 1923.

(Held in the Institution Lecture Theatre.)

Mr. F. Gill, O.B.E., Past-President, took the chair at 6 p.m.

The minutes of the Annual General Meeting of the 31st May, 1923, were taken as read and were confirmed and signed.

The Chairman announced the result of the ballot to fill the vacancies on the Council [see *Institution Notes*, No. 39, page (17) July, 1923], and a vote of thanks was passed to the scrutineers of the ballot.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

The following list of donors was taken as read and the thanks of the meeting were accorded to them.

Benevolent Fund: F. W. D. Adcock; Anonymous; F. J. Baldwin; C. A. Beaton; A. L. Bedford; H. E. Blackiston; E. W. Broadbent; J. E. Calverley; F. W. Capper; H. Cheesman; G. D. Clegg; C. H. Colborn; A. C. de Oliveira; E. T. G. Donovan; W. Duncan; F. J. Edgar; A. R. Everest; W. Eynon; L. E. Felix-Smith; C. F. Fowler; A. Graham; J. R. W. Grainge; F. W. Green; E. Greenhalgh; J. G. Griffin; W. E. Haley; E. Halton; J. S. Hasdell; E. A. Hick; G. A. D. Hill; R. S. Hobson; H. Howard; E. I. Hunter; V. R. Hurle; The Informal Meetings Committee (per J. F. Avila); H. B. Jackson; W. G. C. Jackson; L. G. Jeary; A. B. Johnstone; W. H. M. Kelman; H. Kitchen; W. E. Lane; F. A. Lawson; J. Lingard; P. G. Lloyd; G. A. Maquay; F. C. Meaby; A. W. Metcalf; J. Mirrey; A. T. K. Moir; F. Morton; S. R. Mullard; C. A. Newell; G. Nicolson; A. M. Niven; W. H. Parker; A. S. Peek; L. W. Phillips; W. Redman; A. J. Roberts; J. Russell; C. V. Sampson; C. D. Scrafton; J. F. Shipley; J. W. Slorach; J. L. Smith; W. E. Swale; A. M. Taylor; J. A. Troughton; E. O. Turner; R. N. Vyvyan; S. J. Watson; Western Centre (per T. Hood); J. W. Wheeler; H. K. Whitehorn; E. Williams; F. H. Williams; L. E. Wood; T. Wood.

The Premiums and Scholarships [see *Institution Notes*, No. 39, page (18), July, and No. 40, page (21), October, 1923] awarded during the session 1922–23 were presented by the Chairman to such of the recipients as were present.

The chair was then vacated by Mr. F. Gill and taken by **Dr. Alexander Russell** amid applause.

Dr. S. Z. de Ferranti: When one remembers the size to which this Institution has grown; when one recalls the leading position that it occupies in the country and the vast electrical interests that it represents, one realizes, in some small degree, the responsibility of its President. By rights I should have run over the work of the past year and reminded you of all that has been done in the interests of the electrical industry in which Mr. Gill, our retiring President, has of course taken a leading part. On behalf of all of the members I thank Mr. Gill most warmly for all he has done during his year of office. There is one thing in connection with what he has done of which I should like specially to remind you. Everyone to-day is seeking peace among the nations, and all sorts of schemes are being devised for ensuring it. One of the chief means of bringing about this result is, I think, the freest possible intercommunication. Not only do we want easy and fast travelling between all parts of the earth, so that people may see each other and get to know each other better in these busy times, but we want something more than that; we want instant and direct communication with many people. Mr. Gill has done a great deal in the way of recommending the lines that should be followed to obtain a much more efficient international telephonic communication. That, I am sure, has been most valuable work. Mr. Gill is, as you know, an expert on all telephonic matters, and I should say on every means of electrical communication. Knowledge is a great and important thing that carries much power with it; but I think you will all agree with me that there is something greater than knowledge, and that is character. This our retiring President possesses and has shown to a great degree. It is for his good services in this direction that I think we are even more indebted to him than for the technical work that he has done, and I am sure that we shall all remember him for his excellent qualities as a man. I beg to propose: "That the best thanks of the Institution be accorded to Mr. Frank Gill for the very able manner in which he has filled the office of President during the past year."

Mr. Ll. B. Atkinson: It is a very great pleasure to me to second the resolution proposed by Dr. Ferranti. Perhaps I can speak with regard to our retiring President from even closer quarters than Dr. Ferranti has done, because as I have passed through the chair more recently than Dr. Ferranti there are many matters on which Mr. Gill has given me the opportunity of discussion with him and of obtaining mutual help. I can only tell you that at every stage he has given an amount of thought and conscientious care and consideration to our interests as an Institution that it would be very difficult to equal, and I am quite sure could not be surpassed. We have had as President, as has already been stated, a man of very great ability and very ripe judgment, but he has not made decisions hastily—not until he has studied them very closely from every possible angle. A thought came into my mind a few days ago when I was thinking of this the first Institution meeting of the session. I

do not know who it was that said "The hour always brings the man," but I was very much struck, in turning over in my mind the names of the Presidents that I have known, to realize how true that statement is—that the hour always brings the man. If you study the list of recent Presidents I am sure you will agree that every one of them has, because of his particular knowledge, because of his particular activities, or because of his particular powers or abilities, been able to do one of two things—either to perform something which at that moment was badly needed in connection with the Institution, or to give some message and help to the public with the mutual backing of himself and the Institution. The retiring President is no exception to that rule. Dr. Ferranti has already referred to the particular point of interest which strikes me at the moment. In Mr. Gill we have the consulting engineer of a great corporation, who possesses a world-wide acceptance as a great expert, and who was able at the proper moment to make proposals as to European telephonic communication which could not have been made with greater force or ability by anybody else, and which were made, if I may say so, with greater power because he was our President. That strikes me as the last example of the point which I have been emphasizing.

The resolution was then put by the President and carried with acclamation.

Mr. F. Gill: It is difficult adequately to thank you for what has been said. If there has been any success it has been due to assistance received from those who are concerned in the running of the Institution. I should like to particularize to some extent; I owe a great deal during the past year to the Past-Presidents, to the Vice-Presidents, to the Members of Council, to the members of the Local Centre Committees all over the country, to the exceedingly efficient staff which the Institution possesses, and to Mr. Rowell, the Secretary. But that is not all. I wish to say, in the name of the Institution, that we owe a great deal to the electrical Press for their attitude towards the Institution. Due to that help, work for the Institution during the past year has been one continuous pleasure, although it has been hard work. It is very stimulating to the man who happens to occupy the chair to find the amount of help and sympathy that he receives from all the membership. Not only that, but he very quickly learns what perhaps he had not expected at first, namely, that he can count on and that he can call for help, and get it every time. Last year when I spoke to the Institution I said something about ideals of service. If I have been of any service to the Institution I am more than content.

The President then delivered his Inaugural Address (see page 1).

Sir Richard Glazebrook: I have now to propose "That the best thanks of the Institution be accorded to Dr. Alexander Russell for his interesting and instructive Presidential Address, and that, with his permission, the Address be printed in the *Journal* of the Institution." The duty is a pleasant one because I have known Dr. Alexander Russell for many years, and have been closely and intimately connected with him in many interesting and important problems. I have realized during all that time his devotion to the science of electricity; his interest in it, and the efforts he has made to promote it from various points of view and in many directions. It is a pleasure to me to be able to congratulate him at this meeting on sitting in the important chair he now occupies and to thank him for the Address he has given us this evening. There are, however, some elements of sadness connected with proposing this resolution, because I believe that privilege is usually conferred on the senior Past-President who happens to be at the meeting, and it is not altogether pleasant to be reminded how old one is getting. I was very much struck by what Mr. Atkinson said as to the man fitting the occasion; and I suggest to you that on this occasion we have a man who is very well fitted for the position he occupies. Electricity has progressed in the past 25 years, shall I say, at an enormous rate. The difficulties accompanying this progress have become more and more obvious to us all; and I think at the same time it has been more and more realized that, in order to solve those difficulties, in order to help forward the advance, in order to accelerate the rate of progress, it is necessary that those who are responsible for the task should have great powers of mathematical and scientific investigation and ample knowledge of theory, and those are the qualifications of our present President. You have heard him refer in his Address to some of the important problems connected with electricity. You have heard, for example, what he said about cables and the immense voltages that they can now transmit. No one has done more than he has to tell us what is theoretically possible in that direction—to calculate the forces, the stresses, and so on, that arise in the use of these great pressures—and the same remark can be made with regard to many of the other problems that he has mentioned. He has indicated the necessity for their solution; he has himself helped in many respects in the solution as far as it has gone at present; and I am sure that he has thoroughly deserved the distinction that has now been conferred upon him, and that you will desire to thank him for the Address which he has delivered. I beg to move the resolution I have just read.

Mr. C. P. Sparks: It is a great privilege to second this vote of thanks and I ask you to pass it with acclamation.

The resolution was then put to the meeting by Mr. F. Gill, Past-President, and was carried with acclamation. After the President had briefly replied, the meeting terminated at 7.32 p.m.

A DYNAMIC MODEL OF A VALVE AND OSCILLATING CIRCUIT.

By R. C. CLINKER, Member.

(Paper received 20th October, and read before the WIRELESS SECTION *21st November, 1923.)*

SUMMARY.

A mechanical model is described which represents the action of a 3-electrode valve when coupled to an oscillatory circuit. A string moving around pulleys, one of which is driven by a small motor, represents by its motion the current through the valve. The oscillatory circuit is represented by a spring and a weighted pulley. By a mechanical coupling between the spring and a brake on the driving motor the effect of the intermittent current through the valve is obtained, and the system exhibits self-maintained oscillations. A note is added on a "negative resistance" effect obtained with a centrifugal friction governor.

The model described in this paper was the result of an attempt to produce a mechanical system which should demonstrate as closely as possible the action

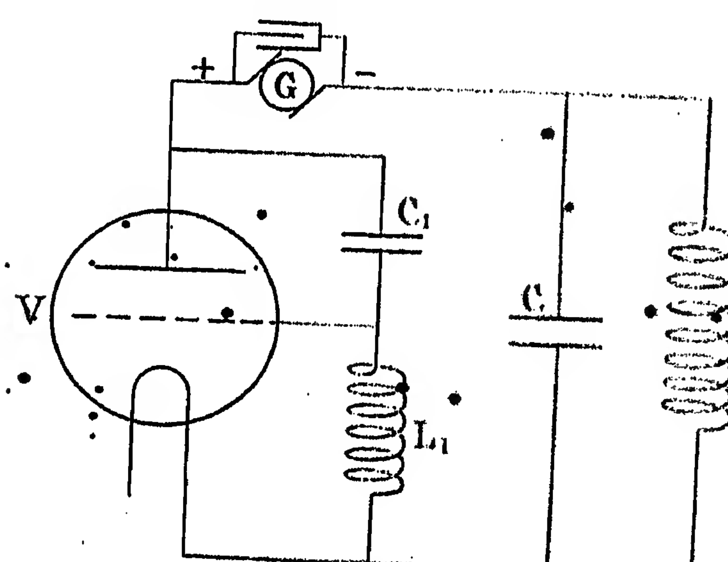

FIG. 1.

of a 3-electrode valve in keeping an electric circuit in continuous oscillation. In devising the model, the author had in mind the dictum of Prof. Jenkin * as to the desirability of a model having some similarity of appearance to the electrical circuit to be illustrated. The model is intended to represent, as closely as possible, the well-known circuit shown in Fig. 1.

Here C and L represent the capacity and inductance, respectively, of the oscillating circuit. G is the source of power. The grid of the valve is capacity-coupled to the anode by condenser C_1.

It will be noted that in this circuit the current carried by coil L includes a d.c. component which passes between the anode and filament of the valve. The two components may be separated by the "shunt" method of exciting the anode shown in Fig. 2, where the main inductance carries only the alternating component.

It would have been preferable in some respects to have made the model represent Fig. 2, but the complications necessary to represent inductance L_2 made it advisable to adhere to the simpler circuit of Fig. 1.

The baseboard, A, of the model (see Fig. 3) is dead-blacked, and upon it is painted a diagram of the circuit, the various parts of the latter being marked underneath the corresponding mechanical parts. A flexible string, S_1, is led round pulleys 1, 2, 3, 4, 5, 6 and 7, of which 3 and 5 are "floating" and the remainder pivoted on the baseboard. Pulley 4 is of large diameter and its mass (together with weights, W, fixed to it) represents the inductance L (Fig. 1). By removing or adding weights, the frequency is varied. String S_1 represents the path of the anode current, and its motion, the motion of the electrons through the valve and oscillating circuit. It passes up in front of the valve V, whose anode, grid

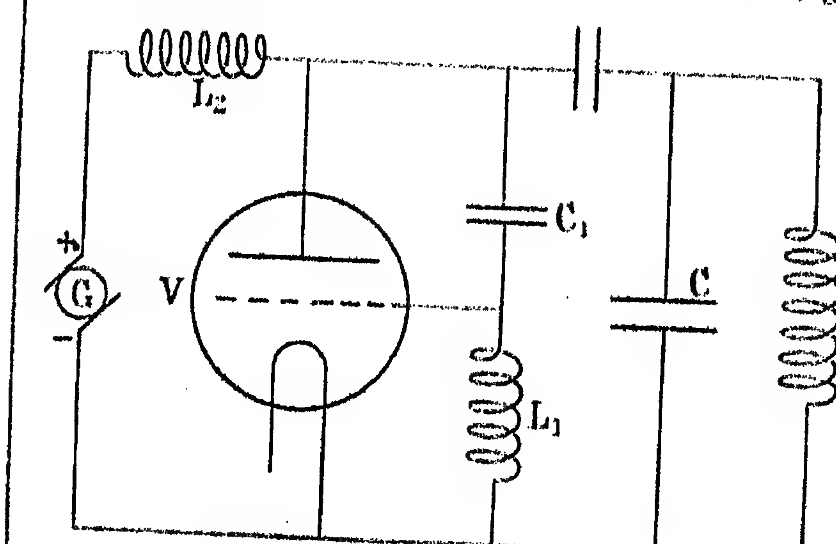

FIG. 2.

and filament are represented in relief by pieces of wood. Another string, S_2, which passes around fixed pulleys 8 and 9, joins the centres of pulleys 3 and 5. The "condenser," C, consists of a flat spring fixed rigidly at D and attached to string S_2 at E. It will be seen, therefore, that the oscillating circuit consists of the mass M, the spring C, and the four pulleys 3, 5, 8 and 9. These four pulleys, and also M, are on ball bearings to reduce friction, i.e. to keep down the resistance of the oscillating circuit. It will be noted that, if string S_1 be held at rest at the valve, spring C and mass M are still free to oscillate. The d.c. source of power is represented by pulley 1, which is driven in a clockwise direction by a small motor behind the baseboard.

A toothed wheel on the shaft of pulley 1 drives a centrifugal governor of the gramophone type. The friction brake controlling the speed of this governor is operated by a thread F, which is attached to a point P on spring ("condenser") C, and passes over a pulley and through the baseboard at the back of which

* See *Journal I.E.E.*, 1922, vol. 60, p. 939.

it is attached to the governor. This thread forms the "coupling" between the grid and the oscillating circuit, and this coupling is varied by sliding P along C. Matters are arranged so that a downward motion of C, i.e. a counter-clockwise rotation of M, draws the brake off the governor and increases the speed of string S_1. The actual grid is represented by a sliding metal strip, G, which is perforated and attached by thread H to spring C. A downward motion of C draws G to the right and uncovers a series of white spots and plus signs, thus representing the grid as "open," or positively charged.

Further, an upward motion of C uncovers a series of minus signs, showing negative electrification.

The action of the model, in mechanical terms, is as follows :—

Upon the motor being started suddenly, string S_1 commences to move. Mass M cannot, however, start instantly. Its lag causes spring C to be drawn downwards, displacing pulleys 3 and 5 to left and right respectively. This action applies an accelerating torque

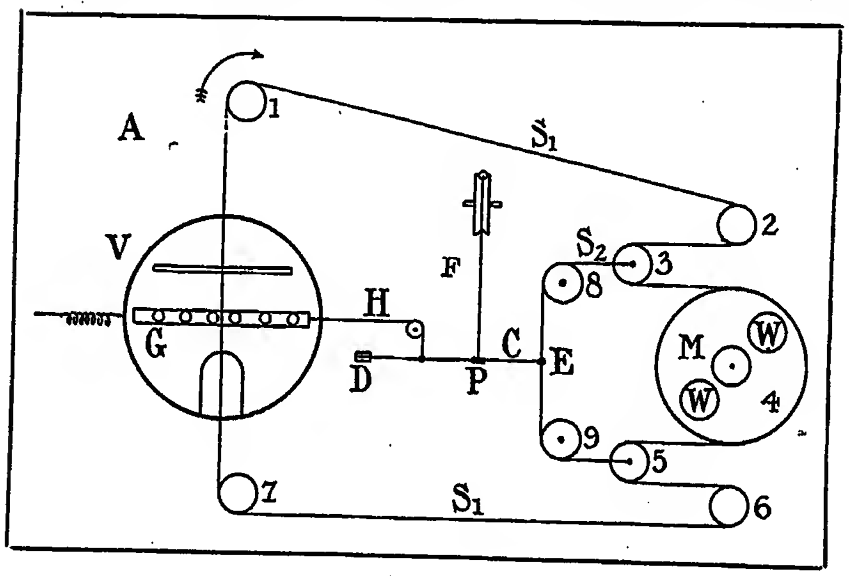

FIG. 3.

to M, and also increases the speed of string S_1 to a maximum, by releasing the governor brake. During this time M gains speed, and E returns towards the centre. When E reaches the centre, however, mass M has a greater peripheral speed than pulley 1, whose speed has been further lessened by the upward motion of E. Consequently E overshoots the central point and, in so doing, applies the brake to a maximum extent and stops pulley 1 altogether. C then returns to the centre, again starting pulley 1, and the operation is repeated, i.e. continuous oscillation is kept up. The string moves forward in a series of jumps, and pulley 4 exhibits an oscillatory motion superposed on a unidirectional one. It is unnecessary to repeat the description of the process as applied to the actual electrical circuit.

By releasing a set screw holding pulley 1 to its shaft, the string may be freely moved by hand, and the experiments described by Prof. Jenkin may be repeated as follow :—

(1) Applying a low-frequency motion oscillates pulley 4, but spring C is not appreciably stressed. This represents the passage of a low-frequency current through the inductance only.

(2) A high-frequency motion passes through almost entirely by means of spring C, that is, a high-frequency current passes through the condenser only.

(3) Slowly reducing the frequency until the motions of spring and mass are equal, demonstrates "resonance." A small motion of the hand produces a large motion of the spring and mass.

It is very interesting, in this last case, to note how much tension has to be put upon the string. This is an excellent illustration of the fact that the impedance of a parallel combination of inductance and capacity is very high at the resonant frequency, if the resistance be low. If L, C and R be the three constants, then the impedance at the resonant frequency is closely equal to $L/(CR)$ ohms, and the combination acts as a resistance having this value.

It is seen also that the phases of the currents carried by condenser and coil are nearly in quadrature with their resultant (the external current). This is illustrated by the model, in which careful observation shows that the maximum velocity of the string through the valve (maximum anode current) occurs at the zero of oscillation velocity (or main oscillating current).

Many illustrations in the mechanical field can be given as analogues of the "negative resistance" property of a coupled 3-electrode valve. The author ventures to add one further illustration, noticed when

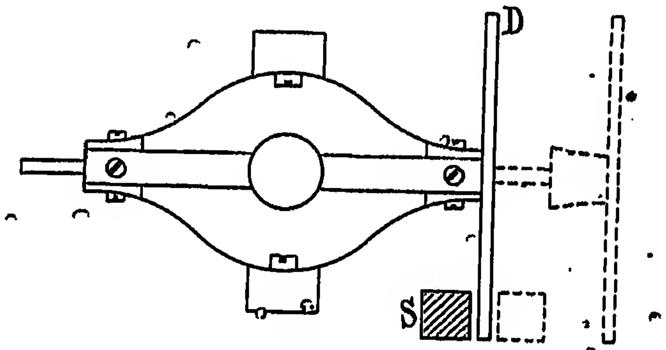

FIG. 4.

constructing the model described. This is provided by the well-known friction-governor mechanism. In Fig. 4 is a diagrammatic view of such a governor. When in rotation, the disc D is drawn along the shaft towards the left hand. If it touches a stop S, a constant speed of rotation is reached because a small increase of speed greatly increases the friction and a small decrease greatly decreases the friction. This results in dynamic *stability*.

But place stop S on the right-hand side and move it slowly towards the disc until it lightly touches. The effect is now opposite to the above. The slight friction retards the motion, reduces the centrifugal force and increases the pressure, thus causing cumulative action which stops the governor. In fact the action is almost instantaneous if S be rigidly held. The result then is dynamic *instability*, and illustrates negative resistance.

It is easy with such an arrangement to produce continuous oscillation, if the stop S is attached to an oscillating system.

In conclusion, the author desires to thank the British Thomson-Houston Co. for laboratory facilities used in preparing the model, also Mr. W. Forbes Boyd and Mr. L. A. Barry for valuable suggestions and help.

DISCUSSION BEFORE THE WIRELESS SECTION, 21 NOVEMBER, 1923.

Mr. G. G. Blake: As the inventor of a valve model exhibited before the Wireless Society of London on 22nd November, 1922, and now used for instructional purposes in the Royal Air Force, I have been particularly interested in the author's most ingenious model. I think that the two models may stand in most friendly relation one with the other. While the author's shows the production of oscillations by a valve, and is a dynamical model, mine shows the effect of incoming oscillations upon the grid of a receiving valve and its plate current, and is a mechanical model, giving actual

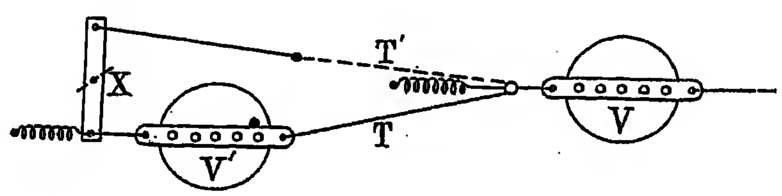

FIG. A.

measurements on calibrated scales. One model appears to me to be the complement of the other. The author's dynamical representation of inductance is very ingenious, while another point which I particularly noted was the reduction of resistance in the oscillating circuit by means of ball bearings. It has occurred to me that, with very slight addition, the "neutrodyne" principle might also be illustrated by his model. As most members will remember, this principle was first employed by Round in his 1913 patent,* in which he showed a condenser connected to the grid to negative the effect of capacity between grid and plate. In 1915 G. W. Wright,† in his dimmed valve limiter, showed an electromagnetic method of balancing out the capacity between grid and plate, and, in 1923, Hazeltine in a paper before the Radio Club of America showed a circuit in which he negatived the internal capacity of the valve by reversed phase capacity coupling, and termed it the "neutrodyne" circuit. A second valve, V_1, might be coupled to valve V of the author's model, as shown in Fig. A, to represent the capacity coupling between two circuits due to the internal capacity of the valve. This coupling could then be neutralized by the addition of a second elastic

* No. 28413/1913.

† No. 8920/1915.

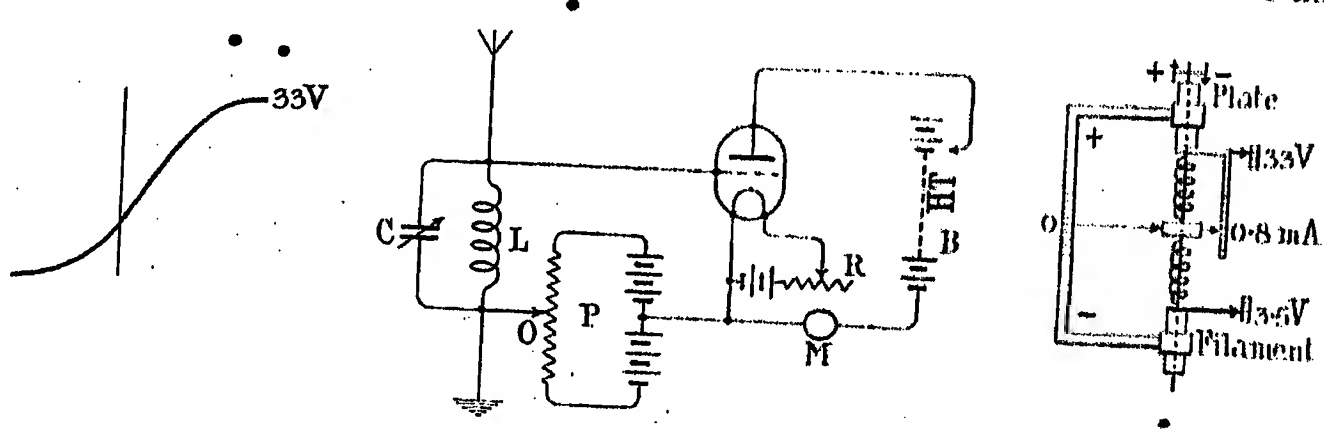

FIG. B.

thread, T_1, acting in opposite phase by means of a pivoted arm X. Another method of illustrating the neutrodyne principle would be to negative the effect of the "coupling thread" F on the model itself and so neutralize the coupling between plate and grid circuits. In a circuit such as that shown in Fig. B there are four variable factors: (1) The grid potential, which can be varied by the potentiometer, O; (2) the filament potential, which can be regulated by the resistance, R; (3) the plate voltage, which can be varied by the H.T. battery, B; and (4) the oscillations produced by the incoming waves in the aerial circuit, CL, which vary the grid potential. There is also a milliammeter, M, in the plate circuit. Fig. C illustrates my mechanical model. A spring, V, is employed to represent the plate current. In the centre of the spring, and attached thereto, is a metal disc, G, representing the grid potential of the valve. On the left is a scale, on which the grid voltages are indicated. It is provided with a pointer P, which indicates the correct position in which the grid-potential disc should be placed to represent various negative or positive values with respect to the filament of the valve. The filament voltage is varied by more or less compression on the lower end of the spring, and the voltages are indicated on a scale. The plate voltage is varied by adjusting the compression of the upper half of the spring, and the voltages are indicated upon a plate-voltage scale. A fourth scale, S, is also provided on which the values of plate current can be read in milliamperes. The values of the scales and the curves represented by the model shown this evening are from a French R valve. The Royal Air Force have worked out similar scales and curves to suit the various types of valve which they employ, and these scales are easily interchangeable for use with the same model. The received oscillations are represented by the movements up and down of a metal rod R, which passes through the centre of the spring V and is coupled to the grid voltage disc, G, by an adjustable slipping contact at the centre of the disc through which it passes.

The oscillations are obtained by means of an eccentric below the rod turned by means of handle H. Adjustment of the eccentric is provided in order to demon-

strate the effect of alterations in amplitude. Two painted arrows (red and white) at the top of the rod indicate the phase. All movements of the grid disc above zero on the grid potential scale represent positive grid potential, and those below zero, negative potential. Referring again to Fig. B (which is reproduced from my paper before the London Wireless Society) the effect of alteration of any of the factors (1), (2) and (3) in the valve circuit can be shown on the plate current, both with the aerial quiescent or when influenced by incoming oscillations, and the action of the valve can be observed when used for amplifying or when recti-

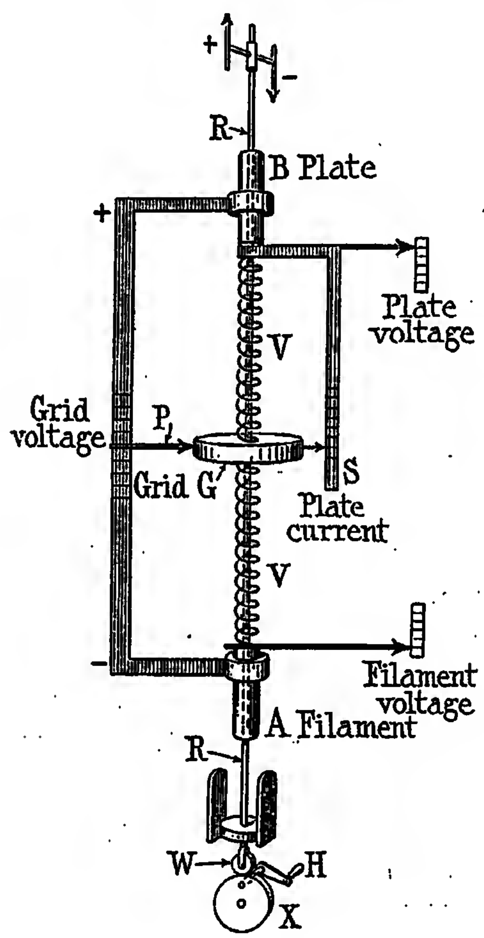

FIG. C.

fying, at different points on the characteristic curve of the valve. The amplification factor also can be demonstrated. Three volts positive on the grid of the valve when the plate voltage is 33 and the filament voltage 3·5, brings us to the top of the characteristic curve, and gives a reading of 1·5 mA. With the grid of the valve at zero, an increase of 21 volts on the plate voltage, making it 54 volts, gives us (when employing the same filament voltage) the same reading (1·5 mA). By dividing the former into the latter we get 7 as the amplification factor. When considering the action of the model it is useful to note that an increase of filament voltage increases the density of the spring coils and makes it impossible for the negative phase of the oscillations to affect the grid-potential disc. This can be likened to an increase of electrons from the filament of a valve, when its temperature is increased, creating a space charge.

Mr. L. B. Turner: The author's model is very ingenious and complete, but I question whether any such model can really assist in explaining the oscillating triode. When (as here) a model must be more complicated than can be grasped by the eye, mathematical analysis must be resorted to; and since one set of mathematical symbols is as good as another, I prefer to deal with the actual quantities instead of others representing them, however close may be the analogy.

Professor C. F. Jenkin (*communicated*): The device of a massive wheel instead of loads on the string is ingenious and allows the direct current to flow. The use of a motor to keep things going is a step ahead. My only criticism is that the condenser and coil C_1, L_1, do not appear to be represented in the model, but I am not sufficiently familiar with the circuit shown in Fig. 1 to know if this omission is of any significance.

Mr. R. C. Clinker (*in reply*): I am much obliged to Mr. Blake for his suggestion as to the "neutrodyne" addition. His suggested arrangement, it is true, would enable the action of the neutrodyne in preventing oscillation to be clearly shown. I feel, however, that a model should be as simple as possible.

With regard to Mr. Turner's remarks, I think that whether or not one desires to have a model of an electrical action depends upon whether one wishes to get a physical grasp of the action, or is content to employ the mathematical machine only. Those students (and there are many) to whom a mathematical demonstration does not appeal as being an explanation, invariably endeavour to form a mental picture of what is going on. To such, a model is an invaluable help, so long as the analogy is not overstrained. In the case under discussion, where we substitute a mechanical mass for an inductance coil, and a spring for a condenser, the analogy is so close as to make it seem that we are dealing with the same fundamentals in the two cases—electrical and mechanical. It is frequently difficult for a student to grasp the principle of the so-called "stopper" or "rejector" circuit consisting of an inductance and capacity in parallel. The statement that its impedance at resonant frequency reaches a maximum of $L/(CR)$ ohms does not give him an explanation. A few minutes' handling of such a model, however, when he can actually feel the resistance offered to the hand by the string at one particular frequency, and observe the relative phases of the motions, impresses the principle on his mind with a clearness that no mathematical demonstration can give.

DISCUSSION ON

"DIRECTIONAL WIRELESS TELEGRAPHY IN AIRCRAFT." *

Dr. R. L. Smith-Rose (*communicated*): All those who have had any experience with the operation of wireless direction-finding on stations will not envy the author his work of making this art sufficiently reliable and accurate for aerial navigation. The difficulties inherent in direction-finding stations are by no means few when the latter are on a good site on land, and are all greatly magnified in an aeroplane in flight. Apart from the actual operational difficulties of taking steady readings, the local errors due to the machine itself must be investigated and corrected. As is shown in the paper, it is not always sufficient to calibrate the machine on the ground or sea when the direction-finding set is required for use in the air. The effect of the metal work and wires contained in the machine offers a problem similar to that provided by the effect of a ship and several error curves given in the paper, I must express my dissatisfaction at the evidence supposed to show the change in quadrantal error from day to day, e.g. in Fig. 3. The maximum difference in the two curves there given is about 6 degrees, yet a change of about 5 degrees at midday, and a total change of 9 degrees shown in Fig. 14, are attributed to another cause. The effect of bonding all metal joints in the machine to maintain constancy of resistance of all current paths, apparently from Fig. 6, reduces the error curve to about half its original amplitude, and is thus an important result of the investigation. With the error amplitude of the order of 6°, and a fairly constant calibration curve, compensation for these effects becomes a practical proposition. Concerning the effect of harmonics in the radiated wave, the errors indicated by Fig. 13

TABLE A.

Variations in Apparent Bearing of Poldhu ($\lambda = 2 \cdot 8$ *km* "*spark*") *at the* 0930 *and* 2130 *Transmissions over the Year March* 1921–*March* 1922.

Observing station	True bearing	Observed bearings			
		At 0930 G.M.T.		At 2130 G.M.T.	
		Number of readings	Variations in bearing	Number of readings	Variations in bearing
	degs.		degs.		degs.
Bristol	230·6	145	1·8	156	26·0*
Newcastle	205·6	365	5·2	172	32·5
Peterborough	232·7	224	4·0	108	22·0
Teddington	247·9	295	3·7	190	38·3

* Some 400 readings taken on other transmissions from Poldhu during night periods show a total variation of 57·5°.

described recently by Mr. Horton in his paper on "Wireless Direction-Finding in Steel Ships." † In this treatment it was shown that in addition to a deviation in the apparent bearing which varies with the wave-length, due to the structure of the ship, there is usually an accompanying "blurring" or flattening of the minimum with consequent decreased accuracy in observing the bearing. With the Robinson system as described by the author, in which the operation of switching or commutating the connections of the "auxiliary" coil is precisely equivalent to the swinging of a single frame or search coil through a fairly large angle (usually about 30°) through the minimum, this flattening of the minimum would probably be unnoticed, unless the rotating coils are deliberately moved into their minimum position. In connection with the are indeed surprising, for although the fields of the waves of higher frequencies than the fundamental will certainly be modified to different extents by the presence of the metal work of the machine, these fields have little effect on the receiving coil, which is presumably tuned to resonance with the fundamental wave. The concluding portion of the paper deals with the "Daily Variation in Directional Wireless Bearings" which variations are stated to be "of the order of 2° or 3° in this part of the world," although Fig. 14 actually shows a total variation of 9°. It is to be presumed that the results illustrated in Figs. 14 to 18 were obtained at a fixed ground station quite free from any machines, metal work or other surroundings which might cause local errors whether fixed or variable. Unless the fulfilment of these conditions is very carefully attended to, the value of the results as illustrating variations due to some external cause, such, for example, as may be

* Paper by Flight-Lieutenant C. K. Chandler (see vol. 61, page 803).
† *Journal I.E.E.*, 1923, vol. 61, p. 1049.

connected with the atmosphere, is very limited. The most striking thing about this part of the paper is that the author does not appear to have encountered the class of error generally termed "night effect," and his curves show a complete absence of this error, which all other experience has shown to be very much greater in magnitude than the errors in the daytime. For instance, the curves in Figs. 14 to 16 all show their largest error at from one to two hours after midday, and thus in daylight, although the times of observation extend in each case from several hours before sunrise until several hours after sunset. In connection with these curves I should like to ask the author at what intervals the observations, as represented by these curves, were taken. To study the variations in detail, it is important that observations of bearings should be taken regularly at 5- or 10-minute intervals. In Fig. 14, for example, the observations appear to extend from 0100 until 2100, but a great deal of recent experience in connection with 24-hour watches has shown that it is seldom that any transmitting station (except by special arrangement) works continuously for such a period without intervals of from one to several hours, during which much valuable information as to the variations may be lost. During the past three years I have, under the direction of the Radio Research Board, collected many thousands of observations on the variations of the bearings of some 40 fixed transmitting stations. To illustrate the relative magnitude of the variations commonly experienced in this country both by day and by night, a summary of the readings taken on the spark transmission of Poldhu, a station evidently much used by the author, at 0930 and 2130 respectively for the year 1921, is given in Table A. The readings were all taken on Robinson direction-finding sets on comparatively good sites on land.

Many similar examples can be given from the large mass of results, the collation of which is now being carried out. It should also be emphasized that the figures given in the table represent the *extreme variations* in the bearings experienced over a period of one year in the course of daily observation, and such variations are not necessarily of frequent occurrence. In Table B the results of one year's observations of the bearings of various spark transmitting stations at three receiving stations are shown in the form of percentages.

From this table it will be seen that although there is a small number of day readings with an error greater than 2°, the proportion of these of the total is so small as to be practically negligible for many applications of direction-finding. The proportion of readings with a day error greater than 5° is entirely negligible. The errors are seen to be much more common at night, although in this case errors greater than 20° are extremely rare. I can support to some extent the conclusion reached by the author that the variations are small when the transmission is in a N–S direction, but the evidence is somewhat conflicting and needs more confirmation. For example, the bearings of Paris [(FL), spark, 2·6 km], observed at Teddington at night over a period of one year, show a total variation of 6·3°; whereas those observed on Paris [(UFP), continuous wave, 2·4 km], a station in close proximity to FL, show a variation of 22·3° during the same periods. The permanent error of the mean observed bearing in each case is negligible, while the variations in the daytime are of the same order (7°) in each case. The difference may be in some way connected with the change from damped to undamped waves, but the cause is by no means obvious. The theory advanced by the author is, of course, applicable only to daylight variations since it requires an ionization gradient in the lower atmosphere. With the exact data that are now being compiled on this subject, it will shortly be possible to examine quantitatively both this and other theories that have been advanced to explain the various phenomena which are encountered when the radio direction-finder is employed to study the propagation of electromagnetic waves over the earth's surface.

TABLE B.

Percentage Differences of Observed Bearings from the Mean Observed Bearings of Various "Spark" Transmitting Stations, taken over the Year March 1921–March 1922.

Observing station	Day readings: Total number of observations	Day: Percentage of readings with error greater than 2°	Day: 5°	Night readings: Total number of observations	Night: Percentage of readings with error greater than 2°	Night: 5°	Night: 10°	Night: 20°
		per cent	per cent		per cent	per cent	per cent	per cent
Bristol	2 514	1·9	0·08	3 958	21·5	7·5	2·2	0·4
Newcastle	4 749	2·7	0·2	5 169	27·8	7·3	1·3	0·1
Teddington ..	3 785	2·9	0·08	4 192	30·3	7·9	1·5	0·1

Flight-Lieutenant C. K. Chandler (*in reply*): Dr. Smith-Rose objects to the evidence showing the change in quadrantal error from day to day and considers that it is probably due to the daily variation in bearing. It is

pointed out, however, that a change in the apparent position of the transmitting station would produce a permanent error in the quadrantal-error curve equivalent to raising or lowering the base line. In the curves shown, the whole character of the curve changes, showing that a local effect is producing the error. Further, after bonding, these large differences between the curves taken on successive days disappear and accurate bearings become the general rule. Previously, of several hundred bearings taken, only a very small proportion were accurate. Thus, with a properly bonded aircraft the error curve remained constant from day to day, but with no bonding the error curve was constantly changing. The fact that the bonding reduces the maximum error shows that this error cannot depend on the daily variation except in so far as this affects the error curve as a whole.

With regard to the question of the effects of harmonics in the incoming wave, these will only have a large effect when two conditions are fulfilled, viz.: (1) When the metal-work circuits are in resonance with the harmonic in question, i.e. Zx in Equation (11) is small. (2) When the voltage generated by the harmonic in the metal work is large compared with that generated in the directional wireless aerial, i.e. K in Equation (11) is large. Requirement (2) is fulfilled when the whole of the metal-work of the aircraft acts as an open aerial as distinct from a loop aerial. An examination of Fig. 13 will show that the main component of the Milton curve is a sine θ component, indicating that it is produced by the metal-work of the aircraft acting as an open aerial. This open-aerial circuit does not resonate to the fundamental wave used in the case of Fig. 13, as is shown by the curve for Poldhu taken on the same aircraft, with the same wave-length, on the same day, where the main component is a sine 2θ function, indicating that the metal-work is acting as a loop so far as the fundamental is concerned. It is thus considered that the Milton curve is due to the metal-work of the aircraft acting as an open aerial and resonating to one of the harmonics in the heavily distorted wave radiated from the Milton station. This oscillating current in the metal-work will induce a large voltage at harmonic frequency in the D.W. aerial, and therefore cause an error in the bearing. It must be borne in mind that the station at Milton was a spark station having a power of 2 kW and was only 30 miles away from the receiving aircraft.

In connection with the daily variation in bearing of wireless transmitting stations, these are stated in the paper to be of the order of from 2° to 3° as a general rule, since this is the conclusion drawn as the result of some hundreds of readings taken over a period of eight months. The curves shown in the paper give an idea of the maximum variations likely to be experienced and were qualified by the above statement. The requirements for accuracy were carefully attended to and more than one site was carefully selected, the requirements mentioned by Dr. Smith-Rose being duly considered. Further, the observers were continually changed in order to check observations from day to day. The bearings were taken every hour, by special arrangements available at the time, which is much more frequent than can generally be obtained. More frequent readings would of course have been much better, but were unavailable. It is considered, however, that the curves give valuable information as to the kind of errors to be met with and their variations—matters of the utmost importance to the navigator. Some of the variations in bearing given by Dr. Smith-Rose are extraordinarily large. In the author's experience extending over several years no variations of this magnitude have ever been recorded when working on spark stations, and had they arisen it would have been impossible not to notice them. From Table B it is noted that not more than 2 per cent of the readings taken show variations greater than the range included in the errors given in the paper. Might it not be possible that these are in the nature of freaks and errors in observation? When using continuous-wave stations for bearings the variations have been found to be of the same order as those with spark stations. On occasions exceptionally large variations were found, but these were invariably traced to accidental couplings between the directional wireless aerial system and the local heterodyne circuits.

With regard to the statement by Dr. Smith-Rose that the theory put forward in the paper requires an ionization gradient in the lower atmosphere, the author does not agree with this, but considers that the gradient is produced in the upper atmosphere and that the whole wave is affected by the refraction of the upper portion. This is borne out by the fact that any ionization in the lower atmosphere would be affected by meteorological conditions. Every effort was made to connect the variations in bearing with meteorological conditions existing between the transmitting and receiving stations, but without any success. It was this consideration that led the author to consider the question of an ionization gradient in the upper atmosphere. The quantitative examination of this problem mentioned by Dr. Smith-Rose should be of the greatest assistance to those engaged in the application of directional wireless to navigation, since it should enable the navigator to make corrections for these variations which are at present neglected to a large extent.

INSTITUTION NOTES.

Annual Dinner.

The Annual Dinner of the Institution will be held on Thursday, 21st February, 1924, at the Hotel Cecil, at 7 p.m. for 7.30. Full particulars will shortly be circulated.

Associate Membership Examination Results: October 1923.

Passed.

Andress, P.	Peasgood, F.
Bailey, G. S.	Pidcock, E. E.
Barrett, H. E.	Rostron, H. M.
Bellamy-Law, J. W.	Sayers, A. J.
Boyland, H. J.	Shaw, C. M.
Clinton, J. S.	Short, O. W.
Davies, J.	Smith, H. F.
Galliard, J. D.	Stinchcomb, E. A.
Godden, L. J.	Tetley, A. C.
Hunter, C. M.	West, F. W. J.
Peakin, C. J. W.	Wolfe, S. S.

Passed Part I only.

Brakenridge, W. D. Morley, E. W. L.
Weir, H.

Passed Part II only.

Buchanan, G. M. King, F. R.
George, J. C. O'Meara, E.

Officers of the Corps of Royal Engineers.

Passed.

Anstruther, 2nd Lieut. A. M.	Malcolm, 2nd Lieut. G.
	Marsh, 2nd Lieut. J. E.
Bickford, 2nd Lieut. E. N.	Miller, 2nd Lieut. C. F. W.
Cobb, 2nd Lieut. E. H. W.	Pain, 2nd Lieut. R. S.
Conlay, 2nd Lieut. R. A.	Paten, 2nd Lieut. L. A. B.
Curry, 2nd Lieut. W. J.	Perowne, 2nd Lieut. L. E. C. M.
Drewe, 2nd Lieut. P. J. L.	
Floyer, 2nd Lieut. M. du B.	Stainer, 2nd Lieut. C. G.
	Stoney, 2nd Lieut. R. F. E.
Francis, 2nd Lieut. H. S.	Toogood, 2nd Lieut. A. F.
Hayden, Lieut. A. B.	Whitman, 2nd Lieut. B. E.
Heard, 2nd Lieut. H. T.	Wilbraham, 2nd Lieut. R. G. V.
Hill, 2nd Lieut. A. J. R.	
Jenkins, 2nd Lieut. J. V.	Young, 2nd Lieut. G. A. D.

International Conference on Large Electricity Supply Systems.

The Secretary has received the following account of the proceedings at the above Conference from Mr. W. B. Woodhouse, who attended it as the senior delegate of the Institution:—

The second International Conference on this subject was held at Paris on the 26th November, 1923, and following days under the auspices of the Union des Syndicats de l'Electricité. Representatives of the following nations were present:—

Austria, Belgium, Canada, Czecho-Slovakia, Denmark, France, Great Britain, Holland, Hungary, Italy, Japan, Norway, Poland, Russia, South Africa, Spain, Sweden, Switzerland, Turkey and United States of America.

The official representatives of the Institution were Messrs. W. B. Woodhouse (senior delegate), P. V. Hunter, C.B.E., and E. B. Wedmore. Other British engineers were present, including Mr. A. Page who represented the Electricity Commission.

A large number of Reports were presented and discussed dealing with problems in connection with the generation of electricity, the construction and operation of transmission systems, and with statutory regulations for securing the safety of the public and continuity of supply.

The British delegates presented three Reports:—

(1) Summary of Recent Researches in Great Britain relating to overhead Line Material and Construction, by Messrs. E. B. Wedmore and W. B. Woodhouse.

(2) Summary of Researches on the Heating of Buried Cables, by Messrs. P. V. Hunter and E. B. Wedmore.

(3) Report on the Earthing of the Neutral Point of High-Voltage Systems, by Mr. J. R. Beard.

The reports and discussion covered a very wide field, and there is little doubt that the discussion of these subjects by so representative an international body will be most beneficial in promoting general agreement as to methods to be adopted and in standardization of practice.

The Conference, as in the case of the first Conference held in 1921, was followed by a meeting of the International Electrotechnical Commission, and the harmonious working of these two bodies will, no doubt, be very beneficial.

During the Conference a number of the foreign engineers were presented to M. Millerand, President of the French Republic, among them being Messrs. Hunter, Borlase Matthews, Page, Wedmore and Woodhouse.

W. B. W.

AN INVESTIGATION OF THE FRICTION BETWEEN SLIDING SURFACES, WITH SPECIAL REFERENCE TO THE EFFECTS PRODUCED BY ELECTRIC CURRENTS PASSING ACROSS SUCH SURFACES.*

[Abstract of Thesis accepted for the Degree of Ph.D. (Science) in the University of London.]

By H. Monteagle Barlow, B.Sc.(Eng.), Ph.D., Student.

(*Paper first received 27th August, 1923, and in final form 22nd January, 1924.*)

Summary.

It has often been demonstrated that when an electric current is passed across certain sliding contacts the friction undergoes a change. In most cases the flow of electricity across the junction is accompanied by an increase in the friction, but in a few instances a slipping action is produced. Both these effects have been applied to the operation of telephone devices, etc., but only a tentative explanation has so far been given of many of the complicated phenomena with which they are associated. In this paper are described a number of experiments designed to elucidate these intricate processes, and in the light of these investigations an attempt has been made to build up a comprehensive theory of their action.

Introduction.

It is proposed to divide the experimental work into three principal sections.

In the first the mechanical effects of relative motion between the parts of various contacts will be considered.

In the second the effects accompanying the passage of an electric current between sliding surfaces will be investigated, (*a*) with reference to good conductors and (*b*) with reference to semi-conductors.

In the third some suggestive observations on stationary imperfect contacts will be described.

Survey of Other Work on the Passage of Electricity across an Imperfect Contact.

Edison seems to have been the first to observe an effect due to an electric current passing across a sliding contact. In 1877 † he found that when a platina-faced wire was drawn over a piece of compressed chalk moistened with certain chemicals, e.g. a solution of hydrate of potash, and a current was passed through the contact, the friction of the wire upon the chalk depended largely on the magnitude and direction of the current.

Edison did not attempt to explain his discovery, but it was generally supposed that the effect was due to electrolytic action at the contact. Sir William Barrett ‡ showed this view to be untenable, and pointed out that if the chalk were dry the friction was increased by the passage of a current, and that a similar effect occurred when the chalk was replaced by a piece of brass.

Barrett's work does not appear to have stimulated any further research on this subject, but in 1905 Appleyard * described a somewhat similar phenomenon. When investigating the apparent decrease in the resistance of a piece of press-spahn with increase of voltage between two rigid electrodes he was led to suspect a variation in the pressure at the contacts and thus to the discovery of what he called a "retentive force" between the dielectric and the metal.

In 1917 Messrs. Johnsen and Rahbek † practically re-discovered Appleyard's "retentive force" and showed that strong adhesive forces were developed when a current passed between certain "semi-conductors" and a metallic plate in close contact with such materials.

Heyl ‡ has attempted to measure the variation in the friction forces between iron and mercury when a current is passed across the junction. The damping effect of an oscillating rod dipping into mercury was observed with and without a current passing through the system. No change in the friction as great as 1 per cent was recorded. A similar experiment with a carbon rod gave a decrease in the friction of about 14 per cent, but the effect was attributed to heating.

This summary would certainly be incomplete if no reference were made to the coherer. It is well known that the action of this instrument has been attributed to electrostatic attraction between its parts. Whether this is correct or not still remains an open question, but it must be admitted that its operation bears at least a striking resemblance to Appleyard's experiments on metal-dielectric contacts. A very large amount of work has been done on the characteristic resistance-changes at imperfect contacts, and it would lead us too far afield to discuss this in detail.

In connection with the mechanical forces between the parts of a coherer, accompanying the resistance changes, the work of Shaw and Garrett § is particularly interesting. By a most ingenious device they measured the force exerted between two copper wires when cohering.

Another field of investigation which has yielded some important observations in this connection is included under "short spark discharges." It has been suggested that the minute gaps which unquestionably exist at an imperfect contact assist in the conduction of electricity

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Edison Telegraph Journal*, 1877, vol. 5, p. 189; and 1879, vol. 7, p. 332.

‡ *Nature*, 1880, vol. 21, p. 483.

* *Philosophical Magazine*, 1905, vol. 6, p. 10.

† See *Journal I.E.E.*, 1923, vol. 61, p. 718, for an account of more recent research.

‡ *Physical Review*, 1907, vol. 25, p. 429.

§ *Proceedings of the Physical Society*, 1904, vol. 19, p. 259.

from the one surface to the other. A single-point coherer has no practical existence; it is really a coherer of many contacts, and consequently there must be air spaces at the junction, some partly and some wholly enclosed. The passage of electricity between two electrodes separated by a gaseous dielectric differs from ordinary metallic conduction, inasmuch as both positive and negative ions normally participate. But the nature of the discharge seems to be influenced to some extent by the dimensions of the gap.

After a careful study of the numerous researches on exceedingly short sparks we are of opinion that the balance of evidence is unquestionably in favour of very thin films of gas having an abnormally high conductivity.

As far as we are aware, no experiments have yet been made with high-frequency alternating fields. Some interesting results might be obtained in this direction. The fact that thin films of gas are not good insulators must be recognized if we are to construct anything like a complete theory of imperfect contact phenomena.

Description of Apparatus.

The apparatus was primarily designed to measure the variation in the normal pressure at a sliding contact when carrying a current.

A few preliminary experiments on the force required to separate a copper disc and a piece of lithographic stone having a potential difference between them, had made it abundantly clear that consistent results could be obtained only when the surfaces were sliding over one another. However carefully the contact was made, no two positions of the disc on the stone were sufficiently alike to render definite the force exerted across the interface. But by measuring the variation in the friction forces between the two parts this difficulty is completely overcome, since with suitable damping arrangements the relative disposition of the surfaces in all positions is obviously averaged. With a knowledge of the co-efficient of friction the change in the pressure between the surfaces may be deduced, provided, of course, that the current produces no other effect.

Experience having shown that the most intimate contact was obtained by grinding, it was clearly desirable that the relative position of the surfaces during this operation should be the same as that during the test. Two different arrangements were employed, which we shall distinguish as the "Torsion" and "Steelyard" apparatus.

Torsion apparatus.—This arrangement is shown in Figs. 1 and 2. The sliding parts consisted of two concentric flat rings, (2) and (8), the upper one being attached to a torsion wire (13) and the lower one supported on a horizontal table rotated by a motor. The twisting force due to the friction at their contact was measured by revolving the torsion head (24) until the top ring was brought back to its position when freely suspended.

In view of the fact established by those who have investigated coherer action, that the coherence is enormously influenced by the degree of oxidation of the particles of metal employed, arrangements were made to surround our sliding surfaces with a non-oxidizing atmosphere. This was done by enclosing the active parts in a gas chamber (10) having an oil seal (3) to allow relative motion. All the parts attached to the lower end of the torsion wire were made of aluminium to make the initial pressure between the surfaces as small as possible and to eliminate stray magnetic action. The current was led to the upper contact ring through a mercury trough (15), which offered no restraint to twisting but merely provided additional damping.

The lower end of the torsion wire which was of silver steel had a cross-piece (20) fixed to it, and this could move in a vertical slot cut in the aluminium rod (12).

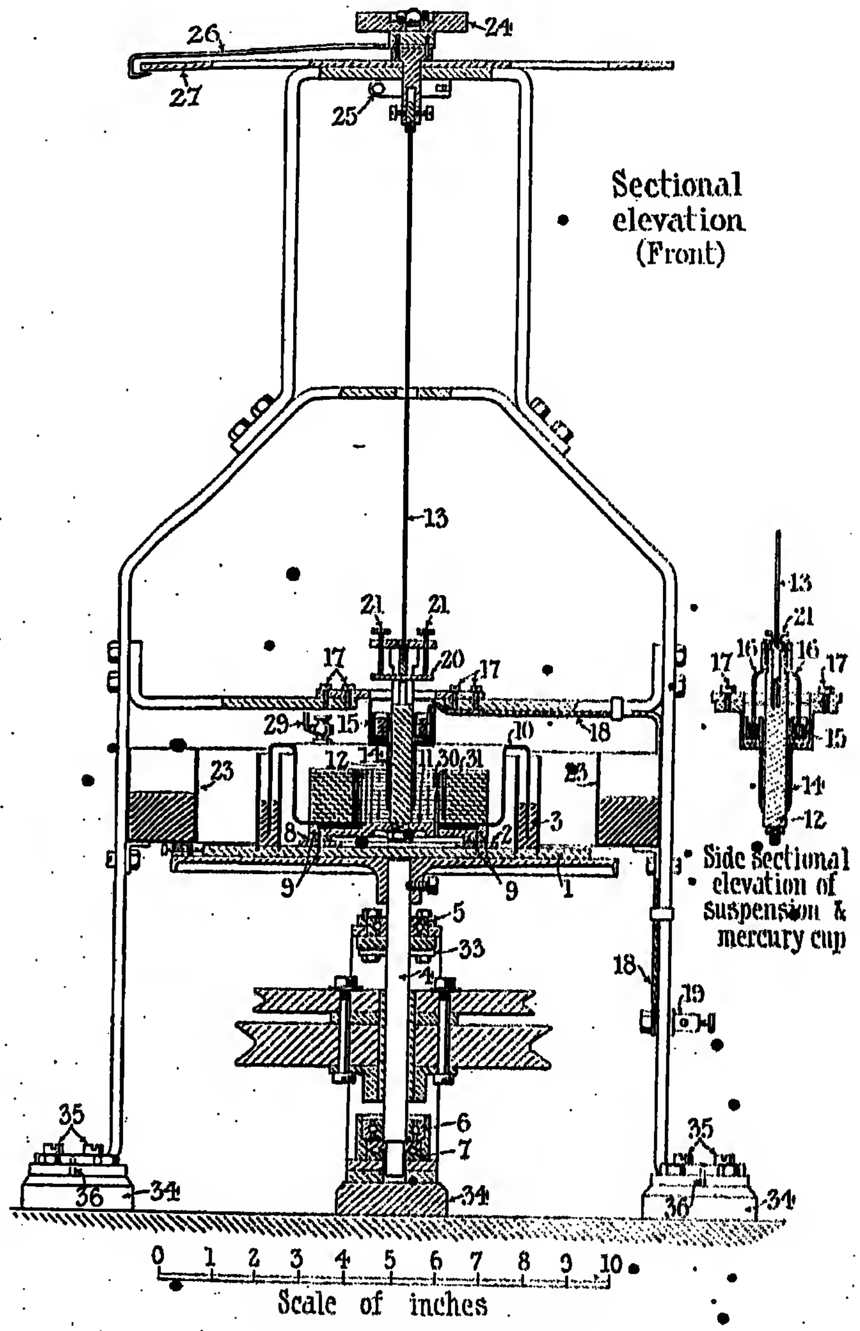

Fig. 1.—Torsion apparatus.

Any change in length of the torsion wire due to twisting or temperature variations was thus automatically compensated for.

Heavy damping was provided by two aluminium arms carrying vanes (22) projecting from the cover of the gas chamber (10) and dipping into another circular trough (23) containing thick oil. Lead weights in the form of rings (31) with a parallel-sided slot, cut from the inner to the outer diameter, were placed in the hollow of the gas-chamber cover so that they exerted pressure directly on the contact surface.

The two parts of the apparatus as a whole were entirely separate and electrically insulated except at the sliding contact. To change the rubbing surfaces the upper parts of the apparatus could be lifted off by removing the four screws (35).

The gas chamber was filled by passing the gas through one of the taps (29) while the air escaped through the rubber tube (30) in the inner diameter of the contact rings.

Two different sizes of torsion wires had to be employed

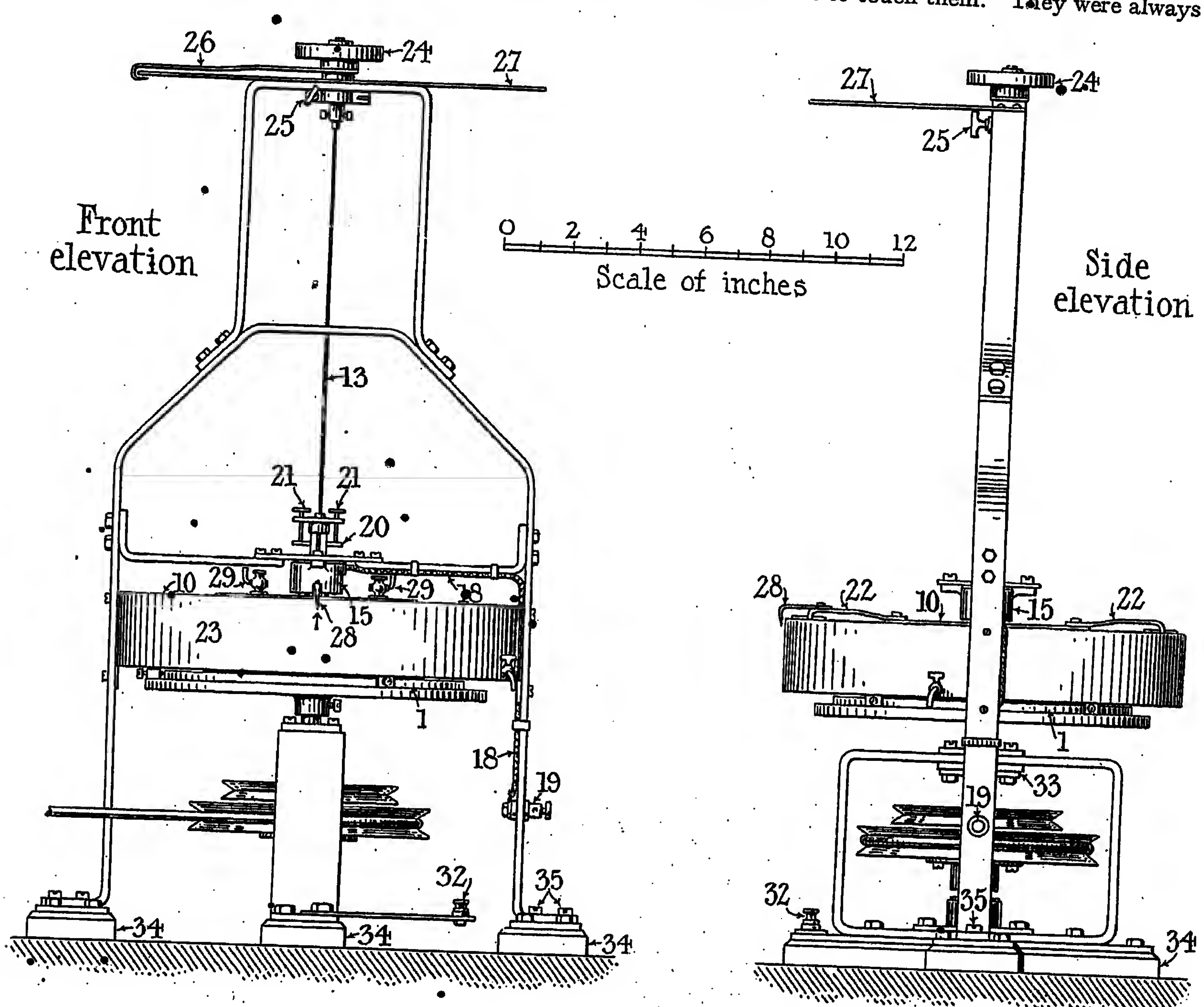

Fig. 2.—Torsion apparatus.

to cover the required range of torque. Both were of silver steel and the same length, but one was $\frac{1}{16}$ inch diameter and the other $\frac{1}{8}$ inch diameter, and they had twisting constants of 1 400 gramme-cm per radian and 22 300 gramme-cm per radian, respectively.

The rubbing surfaces were prepared as follows:—

(1) Ground together in position with flour emery and oil.

(2) Removed from the apparatus and washed with soap and water.

(3) Grinding repeated with very fine carborundum paste until the surfaces assumed a uniform matte appearance.

(4) Removed from the apparatus and washed again with soap and water.

(5) Rinsed in distilled water.

(6) Dried first with linen cloth and then by hot air blast for about 10 minutes to remove dust particles.

(7) Allowed to cool and then replaced in the apparatus.

After the surfaces had been finally washed, great care was taken not to touch them. They were always tested immediately they were cool and, when left overnight, the operations from (4) were repeated in the morning before proceeding with the experiment.

Certain materials required special treatment, which is described when discussing the experimental results.

In all our experiments, except where otherwise stated, we aimed at making the surfaces perfectly dry and clean, having only a discontinuous film of gas between them.

Steelyard apparatus.—The difficulty in obtaining certain non-metals in the form of a ring suitable for testing in the torsion apparatus made it necessary to

construct some other arrangement better adapted to such materials.

The mechanism constructed by Mr. Beauchamp Tower for determining the coefficient of friction of a lubricated journal bearing * suggested the lines on which this design was built up (Figs. 3 and 4).

The semi-conducting cylinder (1) was mounted on a metal shaft (2) and was rotated in a horizontal plane by a motor operating through a reduction gear. On the semi-conducting cylinder rested two brake blocks (17) attached to an aluminium rocker having arms, (18) and (19), projecting in opposite directions. The brake blocks were entirely insulated from one another and from earth, but were connected to two mercury cups (24) through which the current was passed, the circuit being

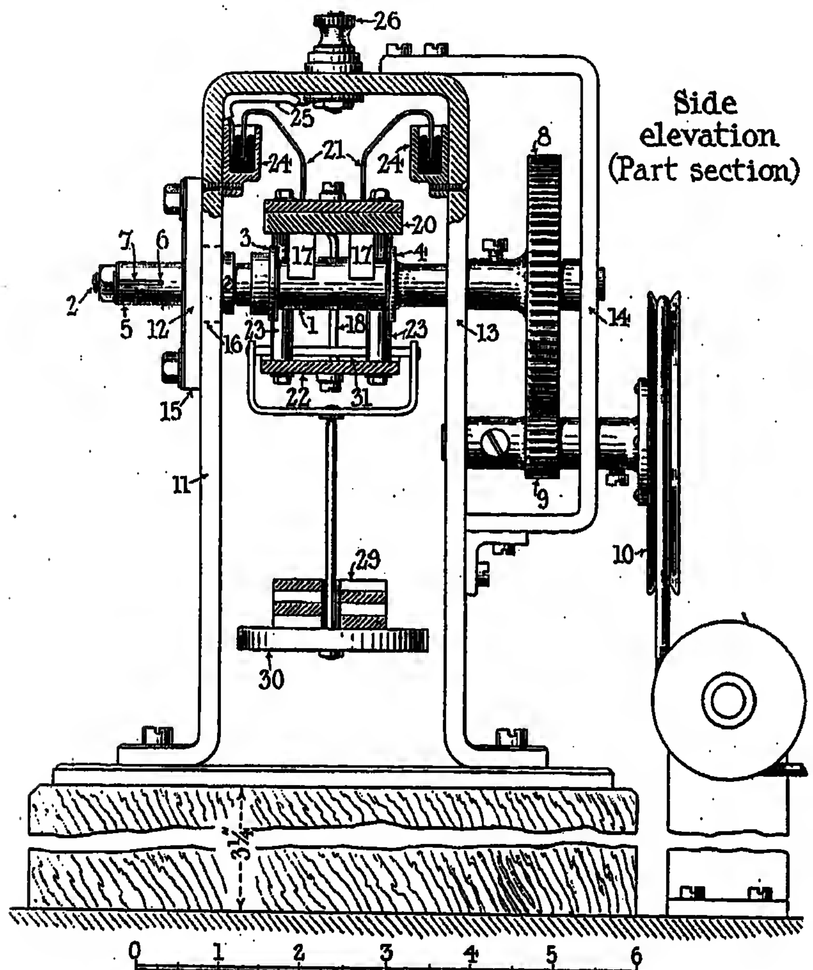

FIG. 3.—Steelyard apparatus.

completed by the semi-conductor. By this means the freedom of the rocker was not interfered with.

The friction forces between the semi-conducting cylinder and the brake blocks were balanced by the jockey-weight (25) on the steelyard arm (19). The other rocker arm (18) carried the damping arrangement, and the pressure applied to the rubbing surfaces could be varied by adding or removing some of the lead weights (29) suspended from a knife-edge (31) on the rocker.

The preparation of the surfaces was much the same as in the torsion apparatus, but under no circumstances were the brake blocks removed from the rocker, or the semi-conducting cylinder from its spindle, until the test was complete.

The position of the jockey-weight when the rocker was exactly balanced was found by temporarily removing the cylinder and replacing it by a horizontal knife-edge on which the brake blocks rested symmetrically.

* *Proceedings of the Institution of Mechanical Engineers*, 1883, p. 632.

Preliminary Measurements and Difficulties.

The first experiments were made on a wrought iron-cast iron contact, and the condition of the surfaces was soon shown to be of the utmost importance in determining the magnitude of the friction-changes accompanying the passage of a current across the junction. The intimacy of the contact, the amount of moisture and foreign matter present, all had a marked influence, and, above all, in the very process of using the surfaces it appeared that they were constantly being changed.

It so happens, however, that when two pieces of dry metal, which have been ground together and carefully cleaned, slide on one another without altering their relative position or the pressure at the contact, the texture of the surfaces does not change uniformly. A state is soon reached when the friction remains very nearly constant, and this continues until suddenly, with practically no warning, seizing takes place.

The duration of the steady state seemed to depend to some extent on the velocity of sliding, and at high speeds it was generally very short. Fig. 5 represents the case of an aluminium-aluminium contact, but the conditions are typical of all metal surfaces. In order to take full advantage of the steady state, the speed of rotation was reduced until the variations in the normal friction forces showed signs of becoming too slow to be properly compensated for by the damping. All the experiments on the metals were made during the constant friction state described above. When seizing occurred the surfaces were re-ground, cleaned and dried again before the tests were continued, and in most cases this operation had to be repeated a dozen times or so. After sliding, the dull matte appearance of the surfaces produced by grinding was partially destroyed. If the contact was good the metallic lustre was restored more or less uniformly over the whole surface.

At first it was thought that something might be gained by polishing the rubbing surfaces, but some experiments on a copper-copper contact showed this view to be erroneous. After grinding the two surfaces together so that they fitted accurately, they were each polished separately with rouge. When replaced in the torsion apparatus and tested in the usual way it was found that they only touched at comparatively few points. The polishing operation had completely distorted them, and the result was a ploughing action which caused seizing.

In many respects non-metals were much easier to handle, chiefly because the steady friction state continued almost indefinitely. In the case of the torsion apparatus the results were found to be exactly the same with and without the gas chamber in use. In view of this fact, the subsequent tests were all carried out in air.

Standards of Comparison.

Since the pressure-change at a semi-conductor contact was found to be principally electrostatic in origin, we

decided that the best basis on which to compare different materials was the drop of potential across the system. In the case of good conductors we had to look to other sources for the cause of the slipping action which is so characteristic of metal-metal contacts. Here the interface P.D. could only be a very small and indefinite fraction of the applied P.D., so that the only reasonable standard of comparison was the current.

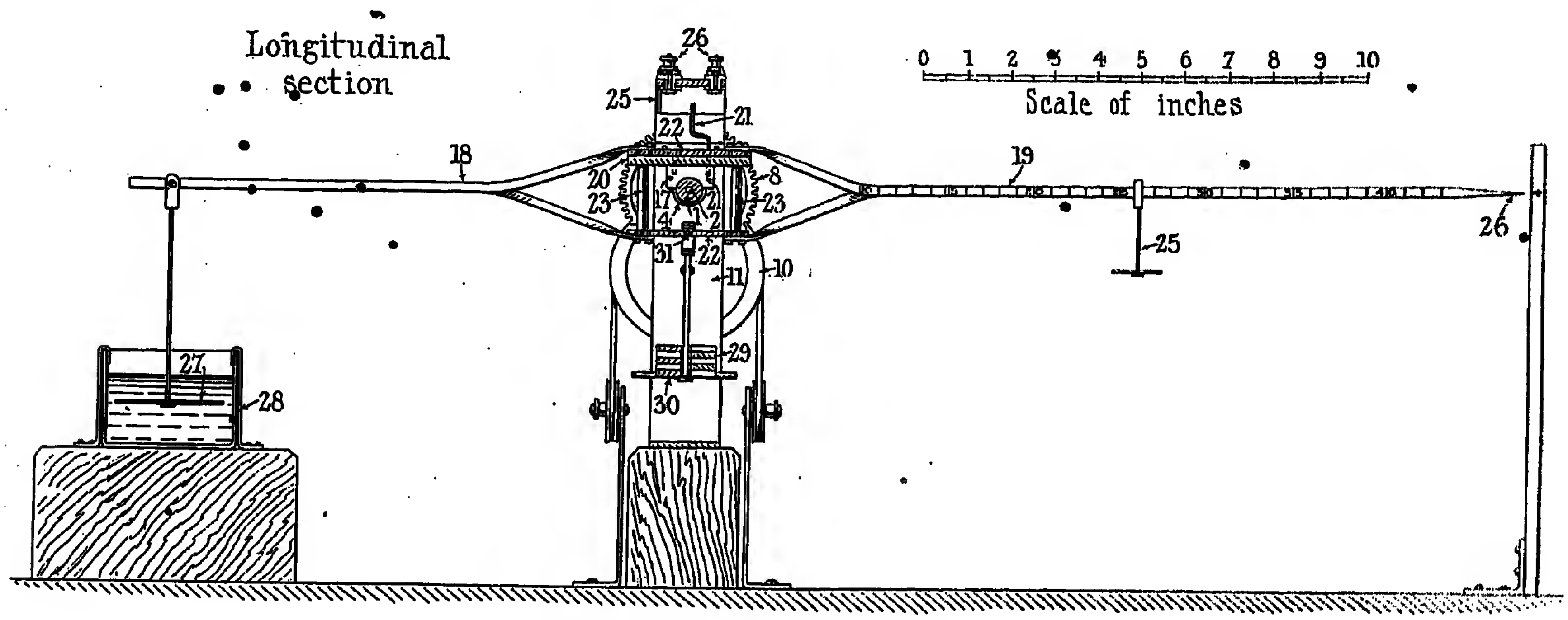

Fig. 4.—Steelyard apparatus.

surfaces, through the tube in the centre. The pressure was kept constant by throttling the output of the blower, and a flexible connection to the gas chamber allowed the air to be passed through while the apparatus was in operation. The temperature of the sliding surfaces was roughly measured by a mercury thermometer at the outlet.

The maximum value recorded was only 30° C., but

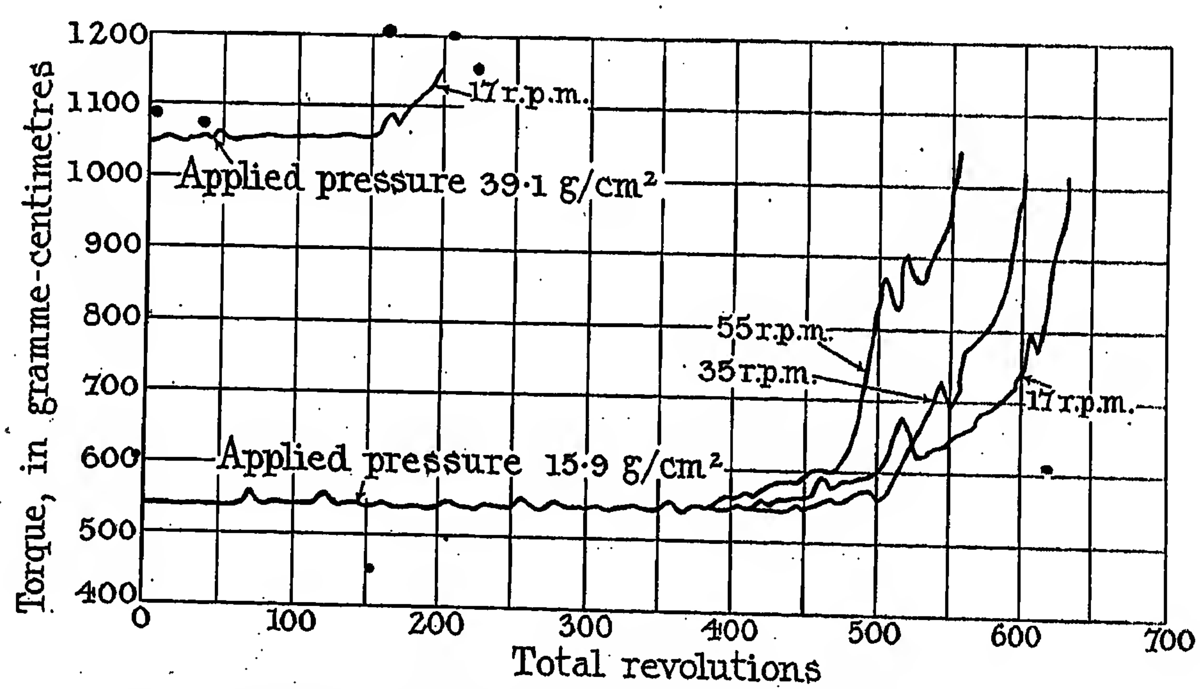

Fig. 5.—Aluminium-aluminium friction, as measured by torsion apparatus.

MECHANICAL EFFECTS AT SLIDING CONTACTS.

Experimental Work.

(1) *Influence of heat.*—A stream of clean hot air was passed through the gas chamber of the torsion apparatus, being admitted by one of the taps on the outer rim and discharged, after passing between the rubbing surfaces over this range the variation in friction was negligible for all the metal-metal contacts. But in the case of copper-graphite there was a decided reduction in the friction forces as the temperature increased, amounting to about − 2·5 gramme-cm per degree C. at a pressure of 18·7 grammes per cm². There were indications that the effect was greater at higher pressures.

The graphite-graphite contact also showed a fall in

friction with increase of temperature, but on a much smaller scale, about $-0\cdot25$ gramme-cm per degree C.

(2) *Relation between friction force and velocity.*—Tests on metal-metal contacts showed a small increase in friction with increase of speed over the range considered, 5 to 100 r.p.m., whilst those including a semi-conductor gave practically no variation.

As an indication of the relation between the static and kinetic friction the following experiment was made on metal surfaces with the torsion apparatus. Having adjusted the torsion head to the equilibrium position for a given steady speed, the motor was shut off and the damping vanes were removed. When the motor was again started, the initial torque in no case exceeded the mean running torque, and was generally a little smaller.

(3) *Influence of surface distortion.*—When a loaded slider is dragged along an elastic plane it will be preceded by compression waves on the surface of the plane. To eliminate any effect due to distortion it is necessary that the slider should be continuous in the direction of its motion. A ring, such as was employed in our experiments, appears to be the only form of slider which satisfies this requirement. But the conditions are very easily altered by cutting radial slots in one of the surfaces.

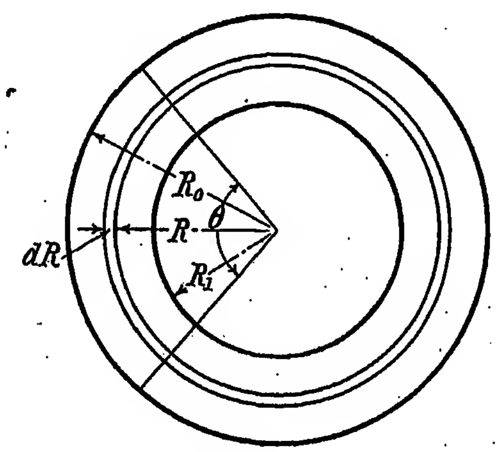

FIG. 6.

Consider a ring, of outside radius R_0 and inside radius R_1, revolving about a vertical axis and rubbing on a flat surface (Fig. 6). If only the area included within the angle θ is operative and the total pressure is P, we have :—

$$\text{Intensity of pressure} = \frac{2P}{\theta(R_0^2 - R_1^2)}$$

Taking an element of area at radius R and of width dR, the elemental friction force dF

$$= \frac{\theta}{2\pi} 2\pi R dR \frac{2P\mu}{\theta(R_0^2 - R_1^2)} = \frac{2P\mu R dR}{(R_0^2 - R_1^2)}$$

where μ = coefficient of friction.

Or total friction torque

$$= \frac{2\mu P}{R_0^2 - R_1^2}\int_{R_1}^{R_0} R^2 dR = \frac{2\mu P}{3(R_0^2 - R_1^2)}(R_0^3 - R_1^3)$$

That is, if T = friction torque,

$$\mu = \frac{3T(R_0^2 - R_1^2)}{2P(R_0^3 - R_1^3)}$$

from which we see that the coefficient of friction for a given size of ring depends only on the slope of the curve connecting torque and total pressure.

TABLE 1.

Calculated Coefficients of Friction for the Various Materials Tested.

Nature of contact	Coefficient of friction	Apparatus employed
Copper-Copper (Area 38 cm^2) ..	0·13	Torsion
Copper-Copper (Area 36 cm^2) ..	0·13	Torsion
Copper-Copper (Area 27·8 cm^2) ..	0·13	Torsion
Silver-Silver	0·12	Torsion
Aluminium-Aluminium	0·14	Torsion
Zinc-Zinc	0·14	Torsion
Wrought iron-Wrought iron ..	0·16	Torsion
Nickel-Nickel	0·16	Torsion
Tin-Tin	0·15	Torsion
Lead-Lead	0·18	Torsion
Steel-Phosphor bronze	0·19	Torsion
Steel-White metal	0·27	Torsion
Copper-Celluloid (Area 38 cm^2) ..	0·16	Torsion
Copper-Celluloid (1) (Area 36 cm^2)	0·15	Torsion
Copper-Celluloid (2) (Area 36 cm^2)	0·16	Torsion
Copper-Celluloid (Area 27·8 cm^2)	0·16	Torsion
Wrought iron-Celluloid	0·15	Torsion
Celluloid-Celluloid	0·18	Torsion
Copper-Lithographic stone (36 cm^2)	0·15	Torsion
Copper-Lithographic stone (27·8 cm^2)	0·14	Torsion
Silver-Lithographic stone ..	0·19	Torsion
Aluminium-Lithographic stone ..	0·2	Torsion
Nickel-Lithographic stone ..	0·16	Torsion
Wrought iron-Lithographic stone	0·15	Torsion
Steel-Lithographic stone	0·18	Torsion
Tin-Lithographic stone	0·15	Torsion
Brass-Lithographic stone	0·22	Steelyard
Lithographic stone-Lithographic stone	0·69	Steelyard
Copper-Slate	0·16	Torsion
Wrought iron-Slate	0·16	Torsion
Copper-Graphite (normal) ..	0·22	Torsion
Graphite-Graphite (normal) ..	0·19	Torsion
Copper-Chalk (saturated)	0·49	Torsion
Copper-Chalk (slightly moist) ..	0·93	Torsion
Copper-Red Fibre	0·12	Torsion
Copper-Paxolin	0·18	Torsion
Brass-Agate	0·29	Steelyard

According to Amonton's law, therefore, it should be possible to cut any number and any size of radial slots without changing the relation between torque and load.

A large number of experiments were carried out in this way on copper-copper ring contacts of two sizes. The area was gradually reduced from the maximum of 38 cm^2 in the one case, and 27·8 cm^2 in the other, to about 0·25 cm^2. The slope of the torque-pressure curves remained practically constant until the final stages were reached, when there was a small but definite increase. Loads up to 3 000 grammes were used, but unfortunately it was not possible to reduce the contact area further and still maintain its proper sector shape.

Prof. Hardy and Miss I. Doubleday say that the coefficient of friction is a maximum when the surfaces are clean, and give the figure 0·74 for a steel slider on a steel plate in this condition.* The coefficients of friction deduced from our experiments on various metal-metal contacts (Table 1) are, on the average, not more than about 0·15. It is true that the same degree of cleanliness may not have been obtained, but even Hardy's lubricated surfaces yield a figure twice as value of the right order. The fact that rings of different sizes gave the same figures is strongly in favour of this argument.

As the result of some careful experiments on discontinuous sliders of various shapes, Chaumat* came to the conclusion that the friction force depends not only on the pressure, as Amonton's law states, but also on the degree of asymmetry of the loading. Hardy has confirmed this result and attributes the effect to irregular lubrication. Is it not more likely to be due to changes in the retarding forces produced by the deformation of the surfaces?

(4) *The significance of the "initial pressure" between the surfaces.*—If the torque due to the friction between the surfaces is plotted against the pressure, we invariably obtain a straight line which, when produced, does not pass through the origin (Fig. 7). That is to say, the friction does not vanish when the applied load is indefinitely reduced, but there always remains a certain

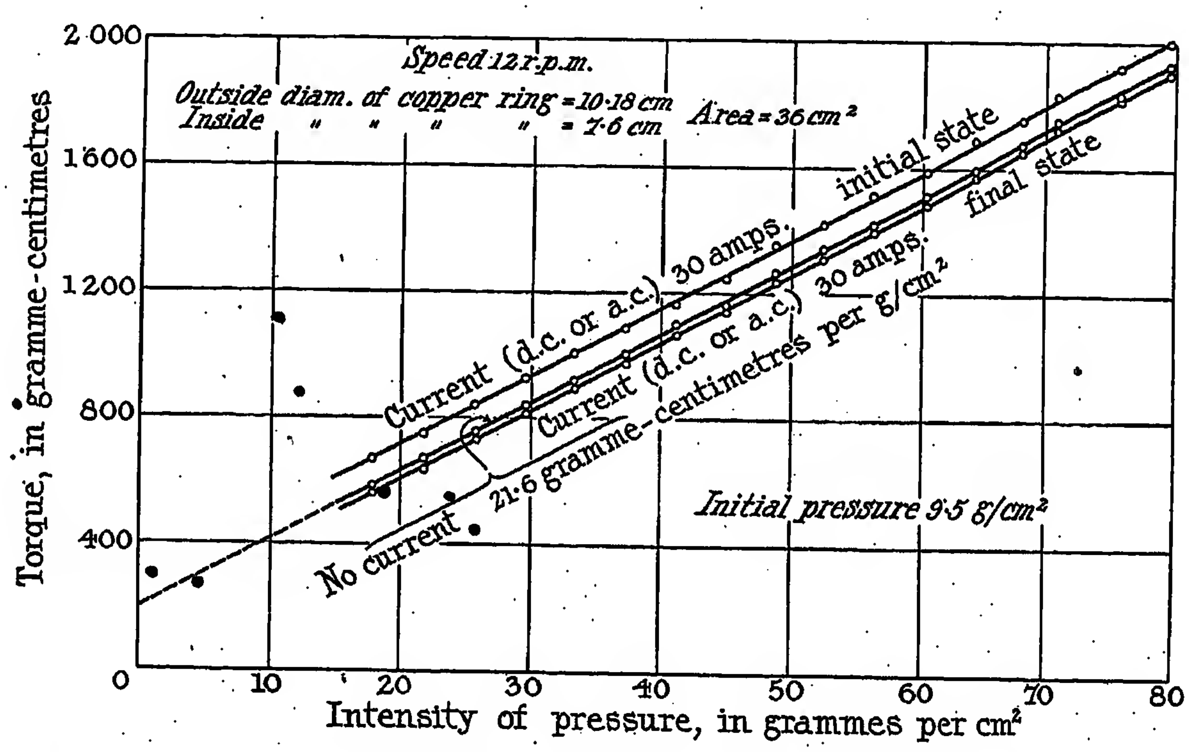

FIG. 7.—Variation of torque with pressure for copper and copper, as measured by torsion apparatus.

great as that which we obtained quite regularly with dry surfaces.

The question arises: Is this discrepancy accounted for by deformation of the contact in the case of the spherical slider employed by Hardy and Miss Doubleday? From a calculation for the maximum intensity of pressure, by the equations due to Hertz † it would appear that the elastic limit of the material must have been closely approached if not exceeded.

It might be objected that our expression for the coefficient of friction of an annular contact assumes the load to be uniformly distributed over the whole extent of the rubbing surface. If the intensity of pressure is greatest near the inner radius of the ring, the calculation will yield an excessive value for μ, or vice versa. We should expect, therefore, an average torque corresponding to what may be conveniently called the "initial pressure" between the surfaces. If the interface was free from moisture, this could only have arisen either (i) from the exclusion of the atmosphere between the surfaces or (ii) from cohesion forces operating at the points of molecular contact. We are inclined to think that the initial pressure is principally attributable to the exclusion of some of the air between the surfaces.

SUMMARY OF RESULTS.

There is plenty of evidence to show that the engaging of asperities is not primarily responsible for the phenomenon of solid friction, although this action undoubtedly amplifies the retarding forces in many cases. Our experiments on surface distortion due to a discontinuous slider demonstrate the effect on a large scale. Its influence is only likely to be of importance with rough

* W. B. HARDY and (Miss) I. DOUBLEDAY: *Proceedings of the Royal Society*, 1922, vol. 100, p. 550; and W. B. HARDY: *Philosophical Magazine*, 1920, vol. 40, p. 201.

† HERTZ: "Contact of Elastic Solids," Miscellaneous Papers.

* *Comptes Rendus*, 1903, vol. 136, p. 1634.

surfaces and high pressures. What we call "seizing" is probably an exaggerated form of surface distortion, and occurs when the elastic limit of the material at the points of contact has been exceeded.

ELECTRICAL EFFECTS AT SLIDING CONTACTS.

Contacts between Good Conductors.

Experimental Work.

(1) *Current-torque changes.*—The change which occurs in the friction torque at a metal-metal contact due to the passage of a steady current is very simple. Fig. 7 represents the case of copper-copper, which is typical of all good conductors. It will be observed that the current does not alter the coefficient of friction but merely adds to, or subtracts from, the pressure between the surfaces an amount depending upon the magnitude of the current passing. Magnetic and non-magnetic metals behave alike in this respect.

The variation of torque with current is much more complicated, although the general characteristics of different contacts are more or less the same. Fig. 8

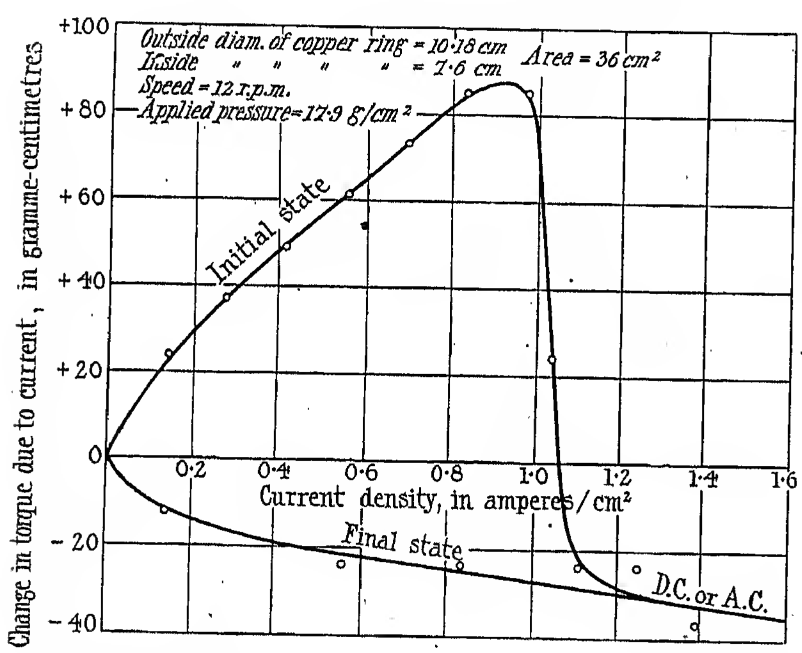

Fig. 8.—Variation of torque with current for copper-copper, as measured by torsion apparatus.

for copper-copper is fairly representative of the average conditions.

After the surfaces have been ground, cleaned and dried, they appear to be in a peculiarly sensitive condition, which we shall characterize as the "initial state." As the current is increased from zero, the friction torque invariably increases, but at a certain critical point the torque suddenly drops and in most cases falls below the no-current value, the drop increasing with further increase of current. If now the current is reduced, the torque returns towards its initial value without any irregular variations. When the current is again increased, the torque-change follows the last part of the first cycle, that is, it generally falls with increase of current. This is the "final state," and its characteristic friction-changes may be repeated any number of times, provided the interval between the tests does not exceed about a quarter of an hour. The "initial state" is always reproduced when the surfaces have been washed and dried, or when they have been left in the "final state" and are not touched for about half an hour. The recovery is gradual and the "initial state" is often partially re-established after a few minutes. If, when the critical current has been exceeded and the "final state" produced, the surfaces are only re-dried in a stream of hot air, the conditions are unaltered, unless sufficient time has elapsed to exercise an influence. Moreover, the "initial state" corresponding to the first part of the cycle can always be repeated any number of times if the current is kept below the critical value.

The actual magnitude of the torque-changes appears

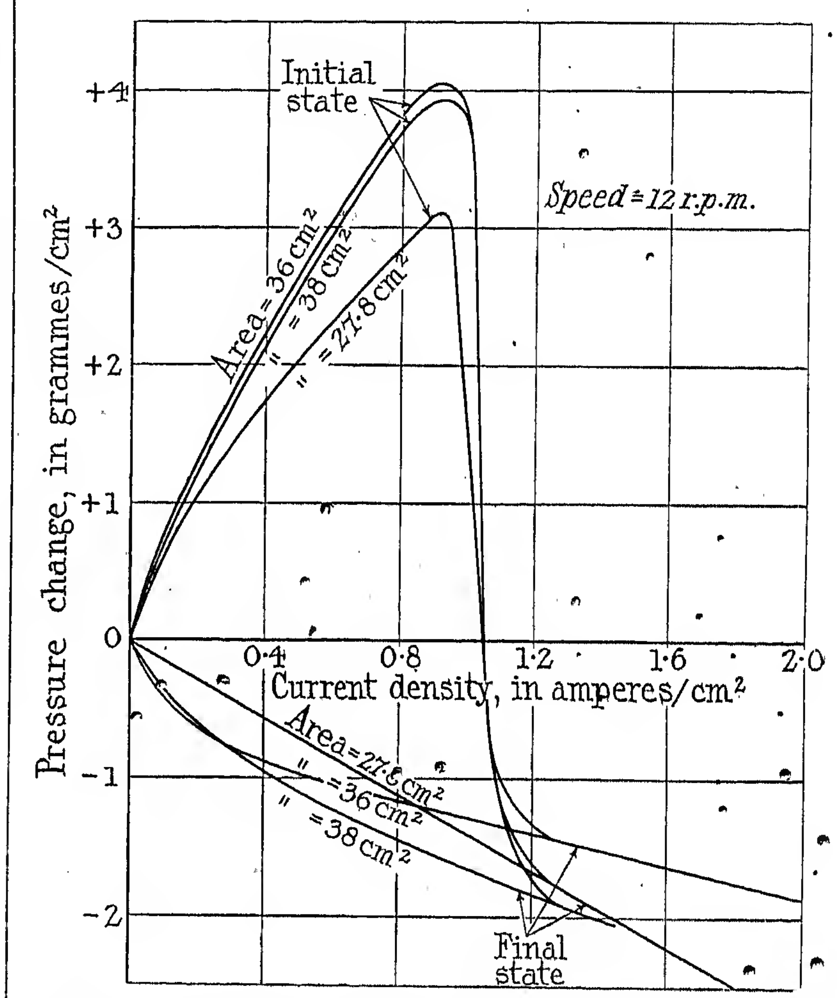

Fig. 9.—Variation of intensity of pressure with current for copper and copper, as measured by torsion apparatus.

to vary with the nature of the contact and the fit of the surfaces. It was noticed that the "stiction" was much more marked when the contact was good.

The full effect of the current does not operate quite instantaneously, particularly in the "initial state." The heavy damping made it difficult to follow the time-changes, especially as these lasted only a few seconds at the most. Even in the "initial state" there always appeared to be a tendency for the current to reduce the friction. On switching on, there was generally a slight transient decrease in the torque, and, on switching off, a similar slight increase. On the whole the observations suggested that there was some building-up action which took a second or two to complete. In all cases the figures represent steady value.

There were also indications that there was a small drop in the no-current pressure between the surfaces at the

transition from the initial to the final state, but the change was scarcely measurable with the apparatus employed.

By combining the torque-current curves with the

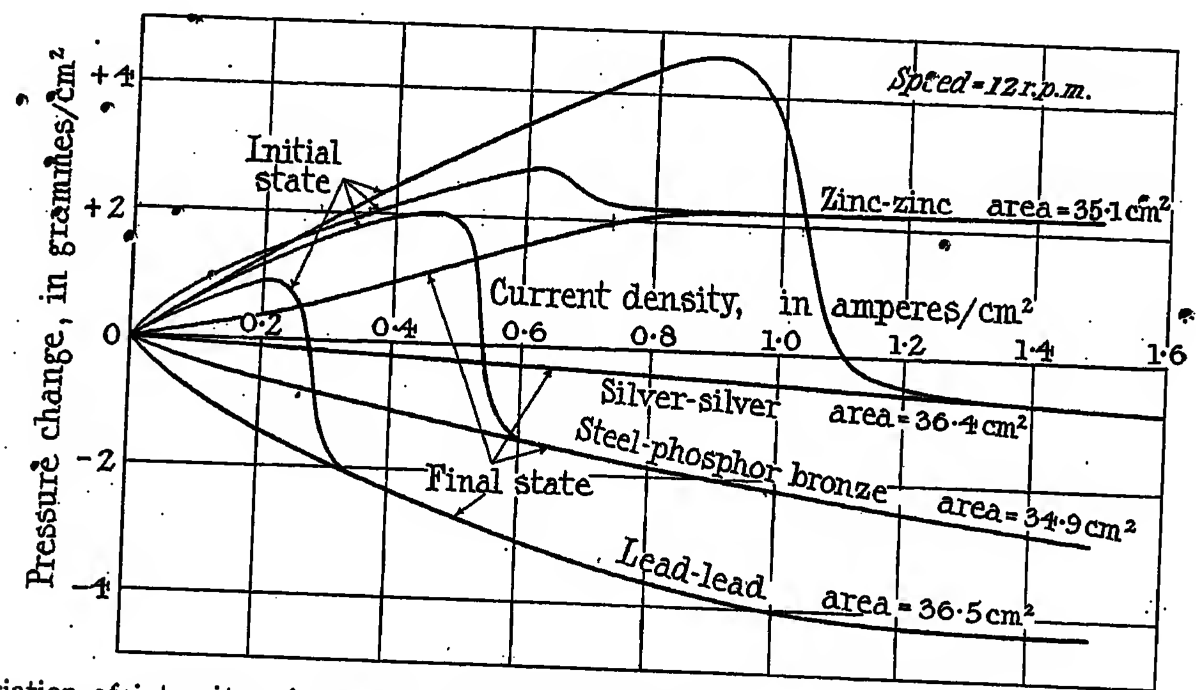

FIG. 10.—Variation of intensity of pressure with current for various metals, as measured by torsion apparatus.

corresponding torque-pressure curves the variation in the intensity of the force across the contact when carrying various currents has been deduced. This was not

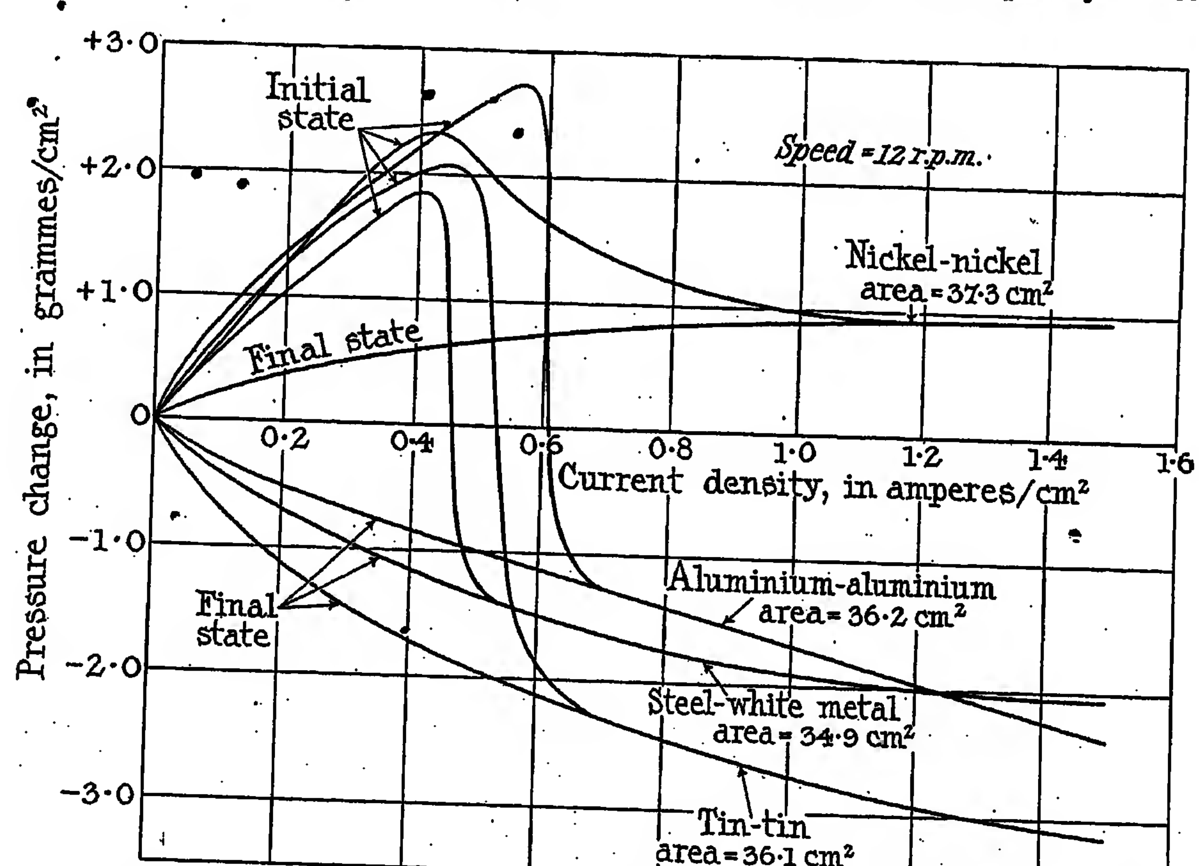

FIG. 11.—Variation of intensity of pressure with current for various metals, as measured by torsion apparatus.

permissible, however, in the case of graphite, on account of the complicating influence of heat. The results are shown in Figs. 9 to 15.

(2) *Influence of electrodynamic action of circuit.*—This effect was proved to be relatively negligible by altering the shape of the circuit so that the loop was very much larger. When the connections to the upper and lower ring extended vertically for considerably greater distances, the changes in the friction forces corresponding to a given current remained unaltered.

(3) *Influence of a liquid film between the sliding surfaces.*—Any trace of moisture between the surfaces enormously reduced the "stiction," and when the interface was really wet a current less than the normal critical value would often cause "slipping." The normal

coefficient of friction was of course also influenced by the water film, which acted as a lubricant, so that a smaller torque corresponded to a given pressure variation, but this does not account for the current effect changing from a positive to a negative one.

Some quantitative measurements were made with a mercury amalgam between two copper surfaces (Table 2). Having secured a good contact by grinding in the usual way, the rings were carefully amalgamated over the whole extent of the sliding faces, so that when placed together in position they formed a continuous metallic conductor without any air pockets between them. Various currents up to 100 amperes were then passed through the system when the two solid parts were in relative motion, and the variation in the friction forces

TABLE 2.

Copper-Copper: Surfaces Amalgamated with Mercury.

Torsion apparatus ($\frac{1}{16}$ in. diam. suspension) calibration 24·4 gramme-cm per degree.
Outside diam. of copper ring = 10·18 cm, Inside diam. of copper ring = 7·6 cm } Area = 36 cm².
Weight of copper ring = 93 grammes. Speed = 12 r.p.m.

VARIATION OF TORQUE WITH CURRENT AT CONSTANT PRESSURE.

Applied pressure = 17·9 grammes per cm².

Current (amps.)	Current density in amps. per cm²	Torque change in gramme-cm
60	1·67	0
70	1·95	− 6·0
80	2·22	− 12·0
90	2·5	− 18·0
100	2·78	− 31·0

observed. The results show that up to about 60 amperes the "stiction" associated with the gas film between the surfaces was entirely banished, and at larger currents a decided reduction in the friction torque was indicated.

(4) *Comparison between different areas of contact.*—Three different sizes of copper-copper contacts were tested, and all gave the same general characteristics (Fig. 9). The relative magnitude of the effects will be discussed later.

(5) *Influence of velocity of sliding.*—There was no measurable variation in the friction effects of a given current over the range of speed considered, 5 r.p.m. to 100 r.p.m.

The total resistance of the circuit also remained practically constant until the sliding surfaces were brought to rest, when it suddenly dropped. Fig. 16 shows the resistance-changes due to motion for various currents passing across contacts of wrought iron-wrought iron, nickel-nickel, steel-phosphor bronze and copper-copper. In all cases the change decreases with increase of current.

To make these measurements an annular mercury trough was fitted to the outer edge of the brass disc on which the lower contact ring rested. An insulated copper

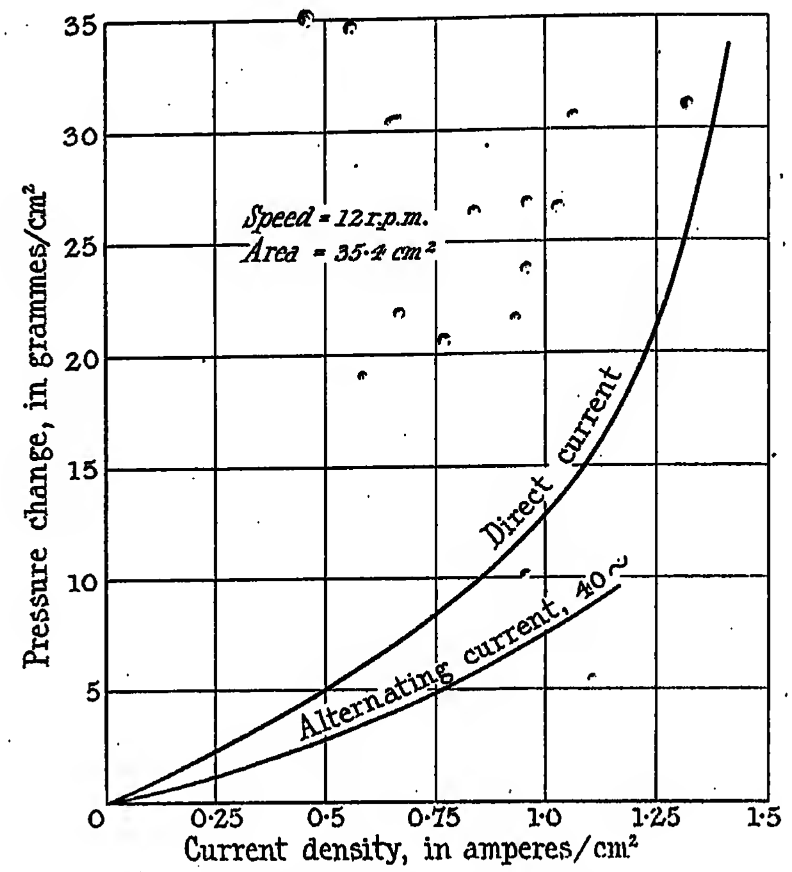

FIG. 12.—Variation of intensity of pressure with current for wrought iron and wrought iron, as measured by torsion apparatus.

wire fixed to the framework and dipping into the mercury trough thus provided a continuous metallic connection

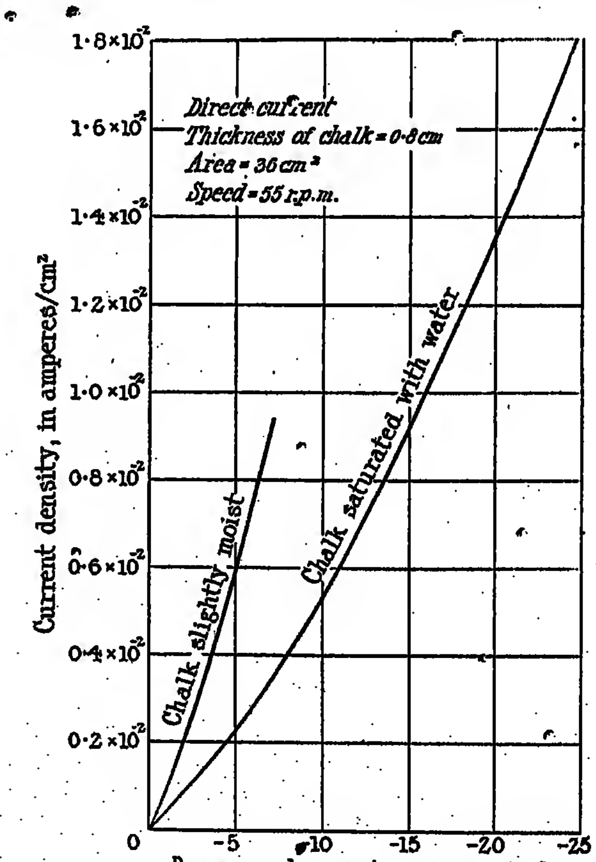

FIG. 13.—Variation of intensity of pressure with current for copper and chalk, as measured by torsion apparatus.

to this ring. By short-circuiting the sliding surfaces it was ascertained that there was no resistance-change

at any of the mercury contacts when the apparatus was set in motion.

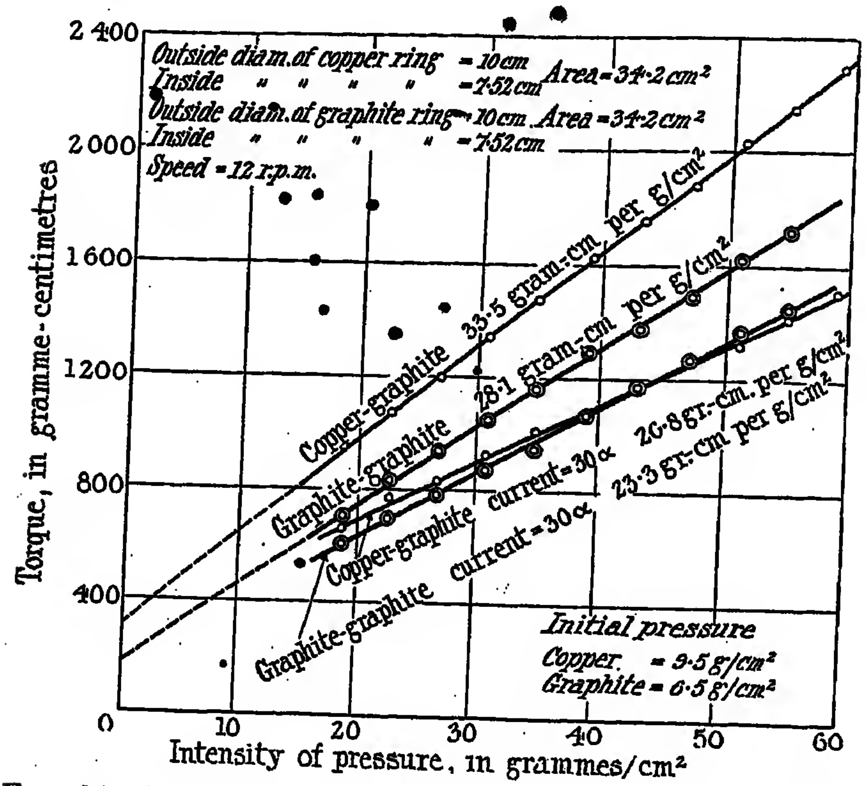

FIG. 14.—Variation of torque with pressure for copper and graphite, and graphite and graphite, as measured by torsion apparatus.

(6) *Instability of resistance.*—This was a very noticeable feature of practically all the contacts tested, and

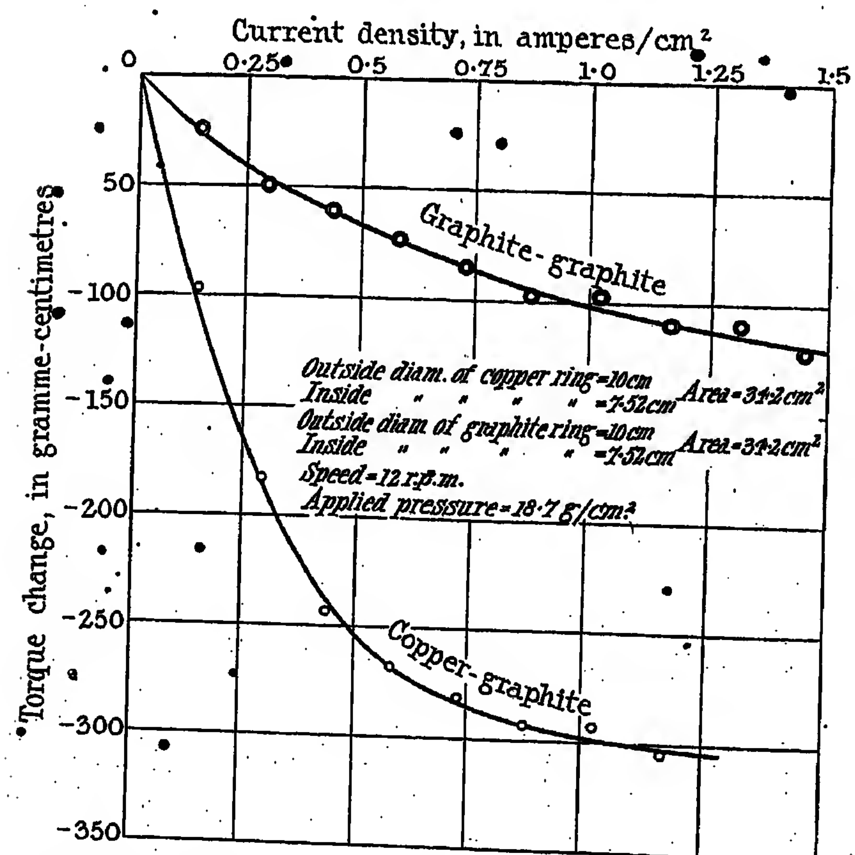

FIG. 15.—Variation of torque with current for copper and graphite, and graphite and graphite, as measured by torsion apparatus.

was in no way associated with mechanical vibration. With a steady applied P.D. the current was continually fluctuating. The effect was perhaps most noticeable when the surfaces were at rest.

(7) *Comparison between the effects of alternating and direct currents.*—Only low-frequency alternating currents (50 cycles per sec.) were employed, but, within the limits of accuracy obtainable, practically no difference was observed between the torque-changes produced by a given R.M.S. value of a varying current, and the corresponding direct current. The initial and final states were precisely the same. There were indications, however, that the "stiction" was not quite as large with alternating current, but the apparatus was not really sufficiently sensitive to decide this point.

These remarks do not apply to the wrought iron-wrought iron contact, which will now be considered separately.

(8) *Effects peculiar to special cases.*

(*a*) *Wrought iron-wrought iron contact.*—The current-pressure changes associated with this contact (Fig. 12)

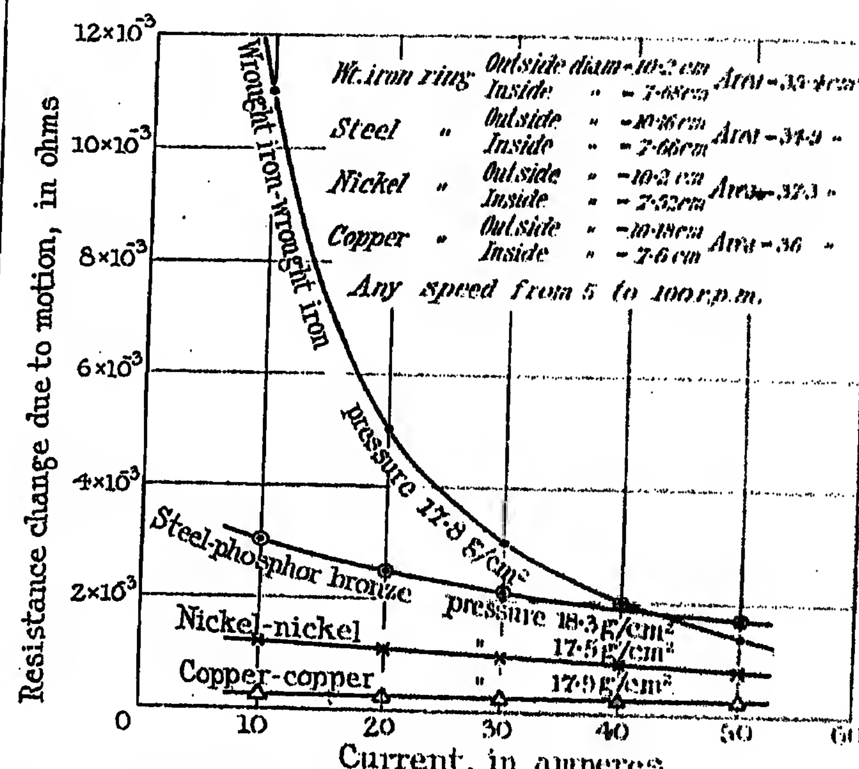

FIG. 16.—Resistance-changes with current between various metals, as measured by torsion apparatus.

differ entirely from those which are so characteristic of all the other metals tested.

There are no initial and final states. The pressure simply increased and decreased regularly with the current, the change being considerably greater than for the non-magnetic materials. The building-up effect was particularly marked, and as much as a quarter of a minute sometimes elapsed before the final steady conditions were reached. Moreover, it was the only case in which an alternating current definitely produced a smaller pressure-change than a direct current of the same value.

The alternating current caused the surfaces to vibrate synchronously, presumably by a periodic variation in the pressure between them.

(*b*) *Nickel-nickel and zinc-zinc contacts.*—These differed from the majority of the metal-metal contacts, inasmuch as the pressure-changes were always positive

(Figs. 10 and 11). The stiction was less in the final state than in the "initial state," and was practically the same for alternating and direct currents.

(*c*) *Copper-graphite contact.*—The fit of the surfaces in this case was perhaps inferior to that obtained with two metals. They were prepared by first grinding with flour emery and water, and then simply allowing them to rub together for some time when slightly moistened. Finally, they were thoroughly dried and tested in the usual way.

No stiction was observed to accompany the passage of a small current across the junction, as Fig. 15 indicates. Possibly the critical current was too small to produce any measurable effect. The "final state" was established immediately and continued indefinitely.

Another peculiarity was that the reduction in the friction due to a given current increased with the pressure applied between the surfaces (Fig. 14).

A considerable amount of heat was generated at the contact when the current was maintained for more than a minute or two, and this seemed to accentuate the slipping effect, the main part of which was simultaneous with the application of the current.

There was no difference between the action of alternating and direct currents.

(*d*) *Graphite-graphite contact.*—The outstanding characteristics of this contact were exactly the same as those of copper and graphite (Figs. 14 and 15). The influence of heat was perhaps less noticeable, and occasionally a small transient stiction effect was observed when the current was first applied.

(*e*) *Copper-chalk contact.*—The friction forces were so irregular in this case that it was difficult to make any observations of value. Small flints in the chalk, which was in its natural state, ploughed the surface of the copper, and to add to the difficulties the current could not be kept constant.

The contact was prepared by scraping the chalk until the marks produced by sliding showed that the fit was tolerably good.

No stiction was observed, and a few preliminary tests made it clear that the effect of a current in reducing the friction was a function of the number of amperes passing and had no relation to the applied potential. There was always an initial rush of current on switching on, and a corresponding drop in the friction torque.

If the current was maintained the effective resistance of the circuit slowly increased, and if the terminal P.D. was kept constant the friction torque gradually returned to its normal value.

When the chalk was moistened, the friction forces became more regular and the results a little more consistent (Fig. 13).

The same current was obtained with widely different applied voltages by varying its time of application, and the curves show that the friction torque is definitely related to the number of amperes passing.

(*f*) *Contact between metallic lead and wood saturated with hydrate of potash.*—This is practically the combination employed by Edison in his original loud-speaking telephone, except that wood was used instead of paper, the surface of which was found to rub up.

It was observed that there was a reduction in the friction when a current was passed across the contact, and that the effect was greater if the lead was connected to the negative side of the supply.

THEORY.

We have seen that the change in the friction at a sliding contact, due to a given current, is independent of both the applied load and the relative velocity. It follows, therefore, that the effect is due to variations in the resultant pressure across the interface.

It is clear that there are two distinct actions involved, one tending to increase the friction and the other tending to decrease it. Certain observations suggest that the effects operate simultaneously in opposition to one another. At a certain critical current, which varies with the nature of the contact, it generally appears that the slipping action suddenly predominates.

(1) *Nature of "stiction effect."*—The increase in the pressure between the surfaces is a necessary consequence of any difference of potential across the interface, and its existence has been practically proved where semi-conductors are involved.

In the "initial state" the "stiction" is by far the more important and, possibly, the only effect.

The irregular behaviour of the wrought iron-wrought iron contact is difficult to understand. We can only suppose that the electrostatic action is supplemented in this case by a magnetic one. The current stream-lines cannot be normal to the plane of separation of the surfaces, so that the encircling magnetic flux crosses the interface at an angle. The relatively high permeability of wrought iron would naturally greatly accentuate this action. The stiction increases much more rapidly than the current, probably because we are working right at the bottom of the magnetization curve for the material.

(2) *Nature of slipping effect.*—It has been shown that the electrodynamic action of the local circuit through the sliding contact had no measurable influence on the pressure between the surfaces, and the effect of the earth's magnetic field must have been equally unimportant on account of the distribution of the conductor to the upper ring. We look, therefore, to the interface for the origin of the observed reduction in pressure between the two parts.

One might suppose a change in the nature of the surfaces by local heating or a small separation of the contact by particles torn away from the solid boundaries. But such considerations are not required by the evidence distinguishing the so-called "initial" and "final" states.

If it is admitted that the numerous gaps between the solid contacts assist in the conduction of electricity across the junction, our selection of the possible causes of the slipping effect is immediately extended.

Many of our results indicate that the reduction in the pressure between the surfaces is primarily a function of the current.

Sir J. J. Thomson * has pointed out that the electric force theoretically required to drag an electron away

* "Conduction of Electricity through Gases."

from a metal surface might easily be realized with even a fraction of a volt across a very small gap. It would seem possible, therefore, that the slipping effect at our sliding contacts was partly due to a bombardment of the surfaces by charged particles projected across the air spaces. A rough calculation is sufficient to show that with currents of the order employed in this investigation such a conception of the mechanism involved is unjustified. The mechanical reaction accompanying the "electric wind" can hardly be supposed to function in the minute gaps with which we are dealing.

Between our rubbing surfaces we probably had both liquid and gaseous conductors through which the current had to pass in crossing the interface. Under favourable conditions the so-called "pinch effect" * may produce considerable mechanical forces between the different parts of a circuit including a mobile conductor, and we suggest that this action is directly responsible for the observed reduction in the pressure at a sliding contact of good conductors when carrying a current.

Whether the film between the surfaces be liquid or gas, the action is much the same. Whether the current is alternating or direct, the forces produced will be practically equally intense. When the interface is wet or bridged by a mercury amalgam we have shown that the initial "stiction" is entirely banished and is generally replaced by a tendency to slip, precisely what one would expect on the assumption that the positive action is due to an electrostatic attraction and the negative one to the so-called "pinch" phenomenon. The liquid film short-circuits the gaps and greatly reduces the potential difference between the surfaces.

Consider the normal case of two metal plates in mutual contact. The interface conductor will in general consist partly of an oxide or sulphide, partly of moisture and partly of gas. For the most part this is mobile and will submit to distortion by striction forces. Although our surfaces were ordinarily dried, it is not to be supposed that they were really free from moisture, and we must regard the gaps as partially occupied by water molecules. The metal will be by far the best conductor and, consequently, the current stream-lines will tend to concentrate at projections on the surfaces. The "pinch" effect will then tend to cause the plates to separate.

Unfortunately, it is impossible to calculate, even approximately, the pressure developed by the "pinch" effect at an imperfect contact carrying a current. We have to remember that the action takes place in a confined space, and that the conducting veins are probably being continually ruptured by a sudden rush of current at one point. When the surfaces are sliding together the conditions are still more complicated. The numerous parallel paths across the contact are continually changing, so that inertia of the interface mobile conductor will have an important influence. The pressure generated by the current in one particular vein will remain some time after it has ceased to conduct, and in this way the total force tending to separate the surfaces may be considerably magnified.

* P. Barry, *L'Industrie Electrique*, 1901, vol. 10, p. 179, and *L'Eclairage Electrique*, 1907, vol. 51, p. 37; also Northrup, *Physical Review*, 1907, vol. 24, p. 474.

The theoretical expression for the pressure produced in a cylindrical conductor, namely

$$p = \frac{I^2}{\pi R^4}(R^2 - r^2)$$

where I = current, and R = external radius, shows that the effect may be very intense over small areas. The conducting veins will contract, and in many cases there will be a complete rupture. If the velocity of displacement is large, the projection of the particles to the right and left of the break may also add to the pressure on the surfaces, and this action will also tend to persist after the current has been stopped and transferred to another part of the contact.

It is interesting to note that A. Sellerio * observed an increased repulsion between the poles of an electric arc when the electrodes were very close together. Further research on this subject might reveal some very interesting facts with regard to the forces accompanying the discharge of electricity across very small gaps.

(3) *The significance of the "critical" current.*—Our experiments have shown that the slipping effect assumes a controlling influence at a certain "critical current." In view of our hypothesis as to the nature of the contact and the action of the interface film, the following explanation at once suggests itself: That the partially conducting layer is suddenly broken down and made a relatively good conductor by ionization. The effect is equivalent to interposing water between the surfaces. The electrostatic attraction forces are enormously reduced by this means, and electromagnetic striction becomes dominant.

In the "initial state" the conduction across the contact is probably mainly through the solid and, perhaps, partly electrolytic. The transition point corresponds to the potential at which metal electrons begin to be dragged across the majority of the gaps, which henceforth assist in the transportation of electricity.

We know that a metal is always more or less spongy, due to the occlusion of air bubbles, and that when the surface is ground some of these are laid open, forming minute pits. When the critical current has been exceeded, these pits will contain ionized gas, which will remain in the conducting state for some little time after the P.D. has been removed. It should perhaps be made clear that the ionization is supposed to be produced through the agency of the electron streams forming the initial discharge across the gaps, and not by the direct action of the electric field.

If, when the contact is in the final or ionized state, the current is switched off, re-combination of the gaseous ions will gradually restore the original conditions. Immersion of the surfaces in water, of course, immediately reproduces the initial state.

We have seen that the full slipping effect does not always operate simultaneously with the application of the current, a fact which is at once explained by the ionization lag. The tendency towards a transient reduction in the friction on making and breaking the circuit, when the interface was in the initial state,

* *Philosophical Magazine*, 1922, vol. 44, p. 765.

may have been an inertia effect accompanying electromagnetic striction in the moisture film before the electrostatic attraction had had time to build up.

On the supposition that friction is due to a lack of correspondence between the direction of sliding and the interface equipotential surface, it is possible that the accumulation of free electricity in the gaps, due to ionization, may slightly modify the distribution of this imaginary frictionless surface. If such is the case the change must be small. We did actually from the fact that the pressure-changes are all approximately of the same order, no deductions of value can be made. This line of investigation was therefore not pursued.

(5) *The relative effects of alternating and direct currents.*—Our hypothesis regarding the nature of the "stiction" and "slipping" effects does not require any great difference between the action of alternating and direct currents where non-magnetic materials are concerned. The observations are, of course, time

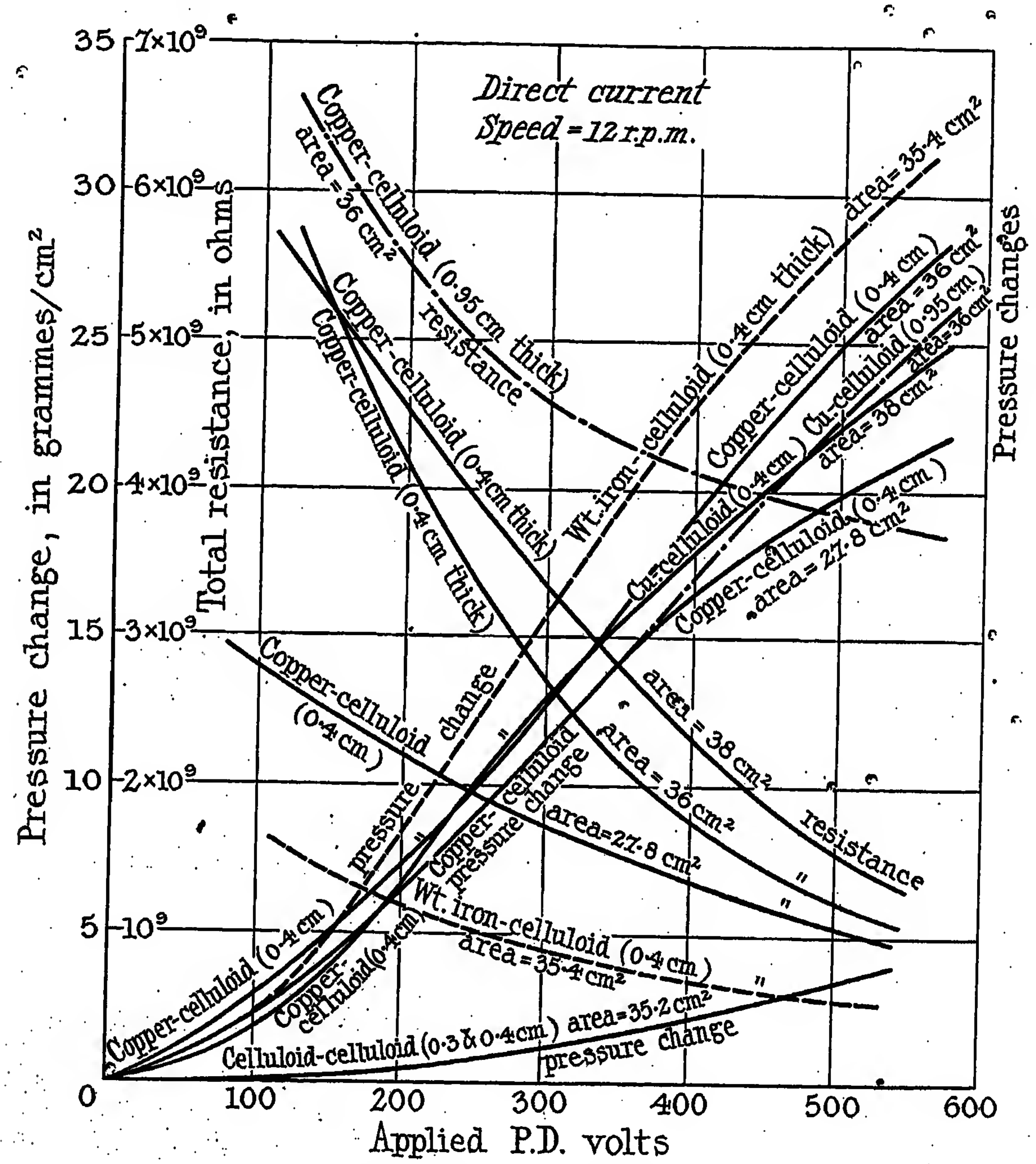

FIG. 17.—Variation in pressure with applied P.D. between various contact areas of copper-celluloid, wrought iron-celluloid and celluloid-celluloid, as measured by torsion apparatus.

observe a slight drop in the no-current torque at the transition from the initial to the final state, but it was scarcely measurable. The coefficient of friction also remained unchanged.

(4) *Influence of the area of contact.*—If in the initial state the electrostatic attraction operated alone the pressure-change corresponding to a given interface P.D. should be independent of the area of contact. We have to remember, however, that the effective transition resistance, and therefore the potential between the surfaces, are actually functions of this area. Apart averages, so that in the case of a varying current the stiction at any rate should be slightly smaller. The magnitude of the effects was unfortunately not large enough for us to get very definite information on this point.

A contact between one magnetic and one non-magnetic metal gave precisely the same results as a contact between two non-magnetic metals, but if both surfaces were iron, the pressure-change corresponding to a given current was very much less with an alternating supply. This is exactly what we should

expect, on the assumption that the effect is partly a magnetic one.

(6) *Contact resistance.*—It is clear from the foregoing discussion that the effective resistance of the interface is fundamentally associated with the friction-changes. In all our sliding contacts the transition resistance fell slightly with increase of current, and the conductivity of the interface film was considerably reduced when the two surfaces were in relative motion. We conclude that the increase in pressure across the contact for a given current is larger during sliding. An examination of Figs. 9 to 11 shows that the critical current varies with the nature of the surfaces. A noticeable feature of the curves is the relation between

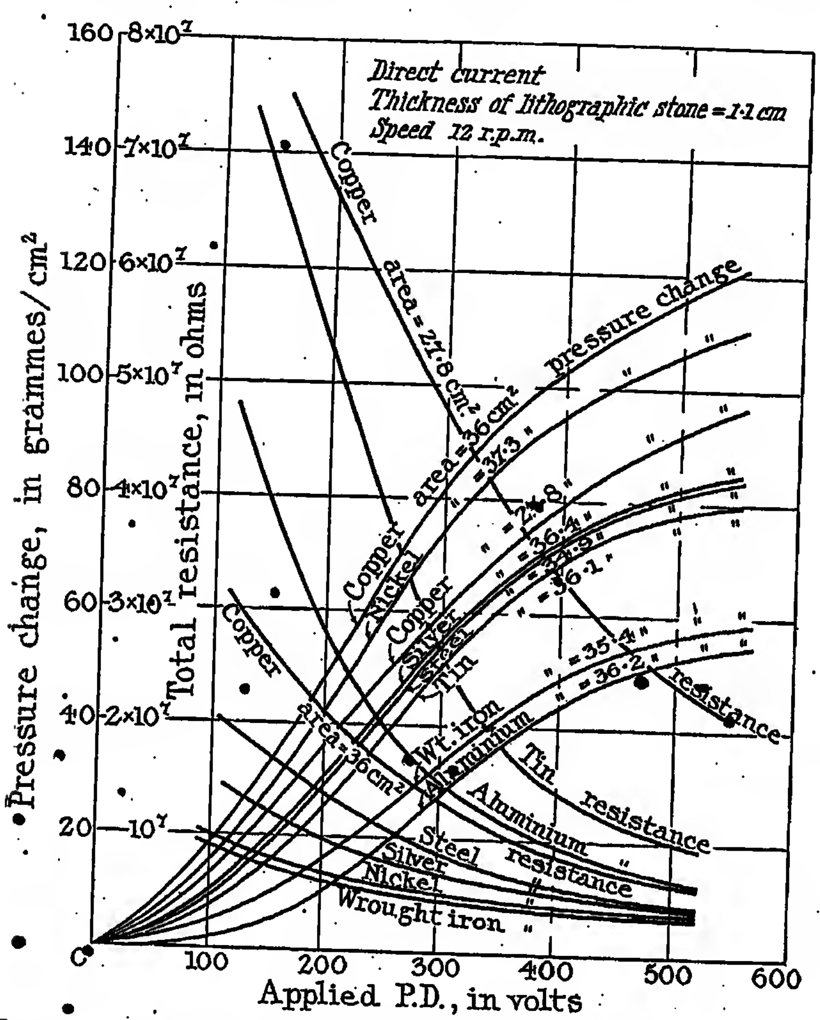

FIG. 18.—Variation of intensity of pressure with applied P.D. between various metals and lithographic stone, as measured by torsion apparatus.

the critical current and the magnitude of the slipping effect. Generally, the greater the one the smaller is the other.

(7) *The influence of the fit of the surfaces on the pressure-changes.*—The larger the gaps, the greater is the tendency towards slipping, principally on account of the rapid reduction in the electrostatic attraction forces.

In the case of copper-graphite, graphite-graphite and copper-chalk, the stiction was completely overcome. On the other hand, in the case of wrought iron-wrought iron, nickel-nickel and zinc-zinc, the slipping effect did not appear. The fit of the surfaces was no doubt partly responsible for these results, but the interface film must also have been an important factor.

Contacts Including a Semi-conductor. Experimental Work.

(1) *Voltage-pressure changes.*—The friction-changes accompanying the passage of a current across a contact including a semi-conductor are very much greater than the corresponding changes occurring at a contact of two good conductors. Moreover, apart from small variations of pressure with the time of application of the current, there are no complicated effects like the "initial" and "final" states observed in the case of metal-metal contacts.

There is always a rapid increase of pressure as the applied potential is increased, up to about 250 volts,

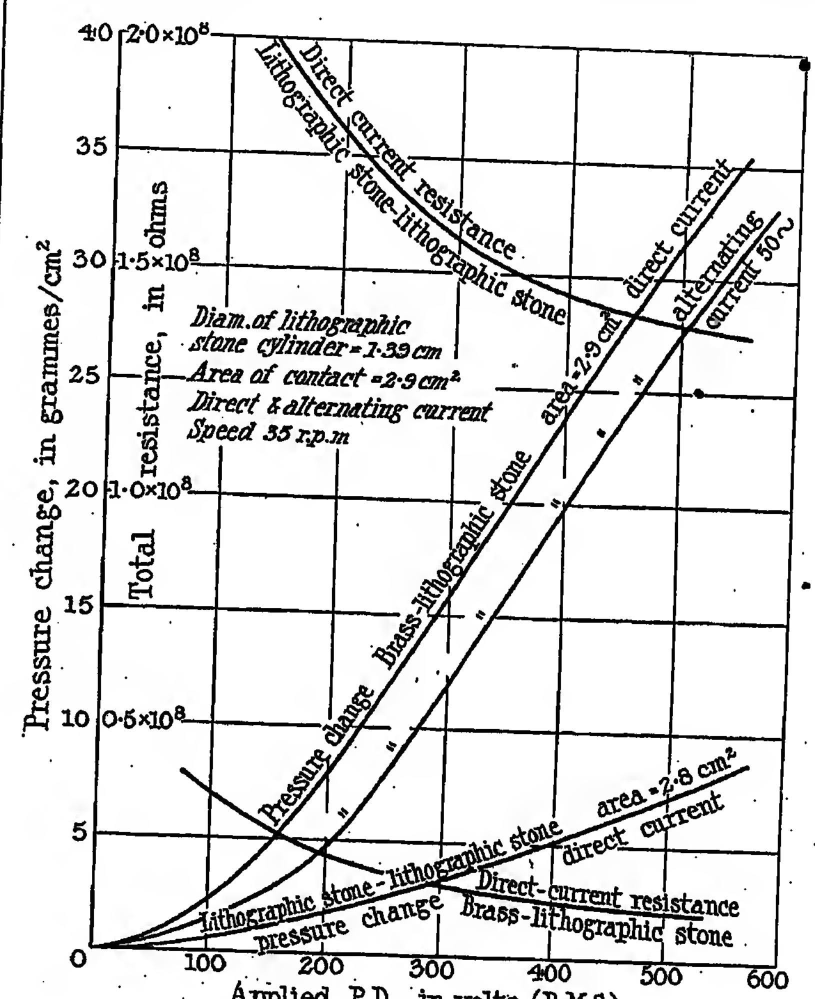

FIG. 19.—Relative pressure-changes corresponding to various R.M.S. applied voltages, as measured by steelyard apparatus.

when the rate of change gradually falls off, forming a point of inflection in the curve (Figs. 17 to 21). The magnitude of the current effect depends both on the nature of the contact and on the thickness of the semi-conductor. Different metals rubbing on the same semi-conductor gave different pressure-changes.

The "stiction" is independent of the force applied between the surfaces, so that a given P.D. merely displaced the torque-pressure curves bodily without altering the coefficient of friction, as in the case of the good conductors.

(2) *Voltage-resistance changes.*—The total resistance of the circuit also varied with the applied P.D. At low voltages it falls rapidly, but tends to a steady value as the potential is indefinitely increased (Figs. 17 to 21).

In many cases it was difficult to get reliable figures for the resistance, on account of its characteristic instability. When the terminal P.D. was perfectly steady, the galvanometer deflection kept jumping up and down, whether the surfaces were in relative motion or not. The effect was exactly the same as that observed with metal-metal contacts. It had nothing to do with vibration, and was generally more marked at the higher voltages.

The pressure-changes appeared to depend very little upon the magnitude of the current passing, and were not perceptibly affected by the resistance instability.

(3) *Variation of torque and resistance with time of application of P.D.*—The total increase in the torque or

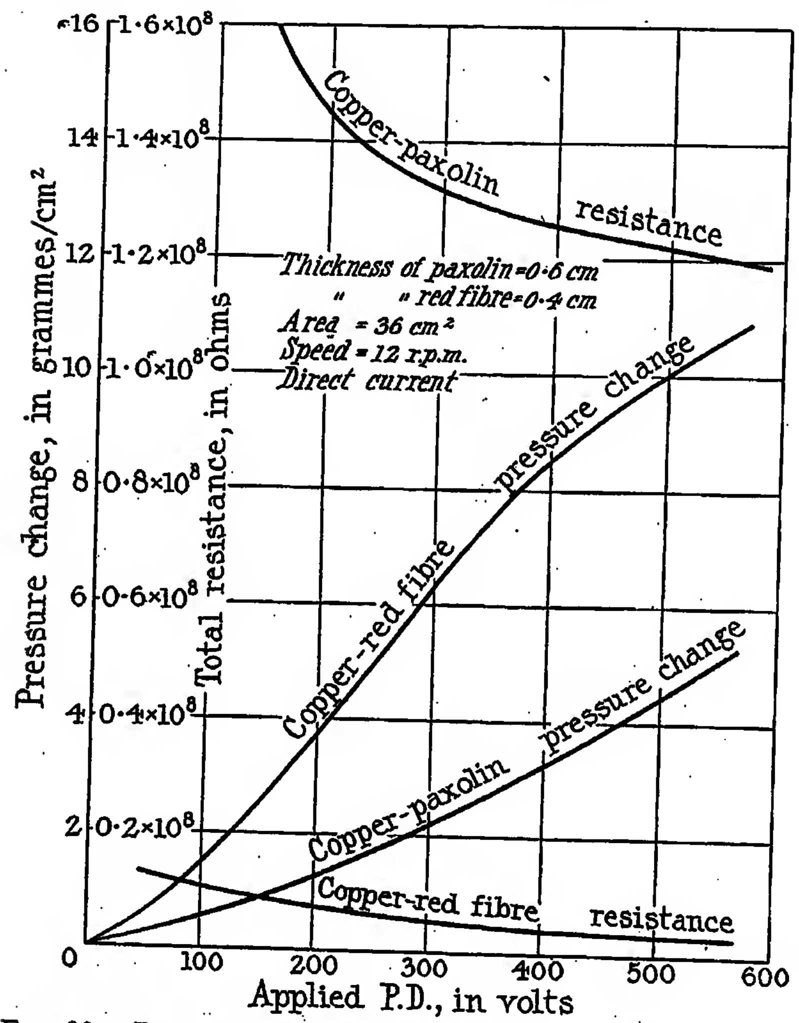

FIG. 20.—Relative pressure-changes corresponding to various R.M.S. applied voltages, as measured by torsion apparatus.

pressure corresponding to a given potential is not usually simultaneous with its application. In most cases there is a lag of a few seconds, the pressure gradually rising to its full value on switching on, and gradually falling to its normal value on switching off. The curves represent final steady values.

In the same way the total resistance of the circuit undergoes a change with time, and usually assumes its greatest average value when the torque or pressure is a maximum.

There are, however, a few exceptions to these generalizations. The contacts of copper and celluloid (xylonite) showed practically no variations in either the torque or the resistance with the time of application of the P.D.

Brass and agate gave a curious directional effect (Fig. 22). In this case, as the torque increased the resistance decreased, and vice versa, the nature of the change depending upon the direction of the current. By repeated reversals when the conditions had become approximately steady, a series of curves was obtained which show the relation between these quantities. The steady value of the torque was independent of the direction of the current, but the effective resistance of the circuit had two final values, according to which brake block was positive and which negative. This asymmetry must have been due to some small difference between the two contacts on the cylinder.

(4) *Influence of moisture between the surfaces.*—When the interface was saturated with water the application

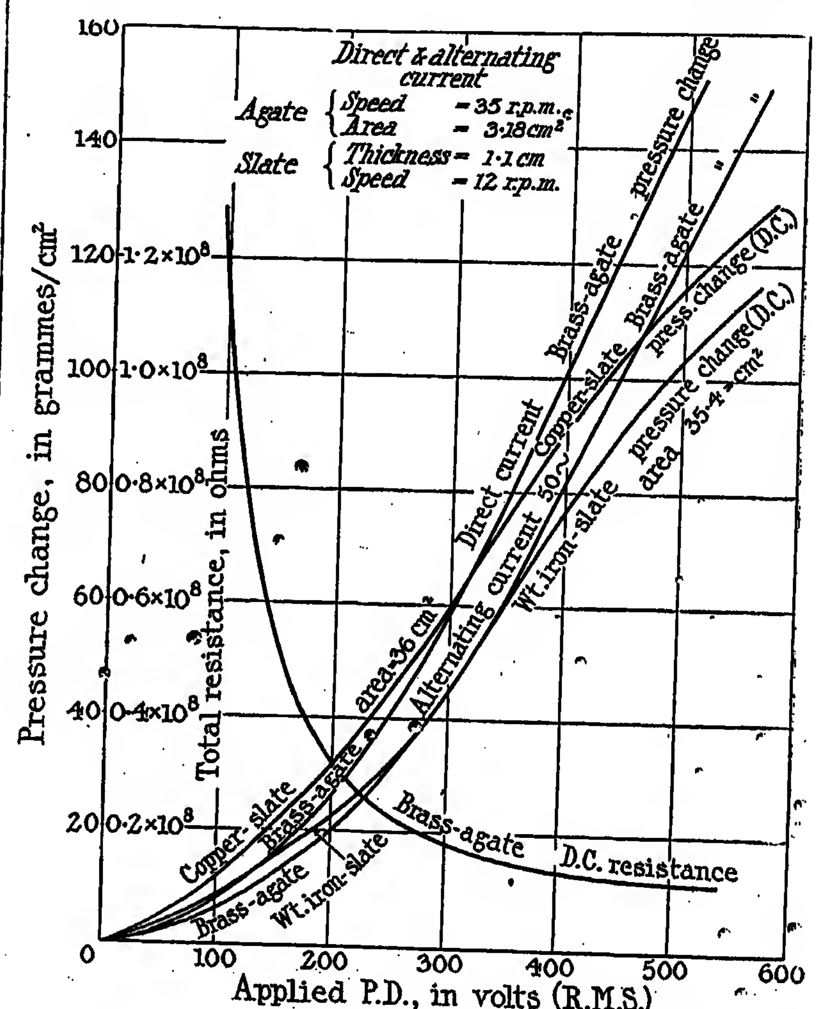

FIG. 21.—Relative pressure-changes corresponding to various R.M.S. applied voltages, as measured by torsion and steelyard apparatus.

of potential differences up to 550 volts produced no observable change in the normal friction forces. This was equally true for all the semi-conductor contacts.

In the case of silver-lithographic stone, the total resistance of the circuit at 550 volts was reduced from about $3 \cdot 9 \times 10^6$ ohms when dry, to about 10^6 ohms when wet. Similarly the resistance of wrought iron and lithographic stone fell from $3 \cdot 1 \times 10^6$ ohms to $1 \cdot 3 \times 10^6$ ohms when water was interposed between the surfaces.

(5) *Comparison between different areas of contact.*—Three different sizes of copper rings were tested in contact with the same sample of celluloid. The results are represented in Fig. 17, and will be discussed later. Celluloid was chosen for this comparison because there

is practically no lag in the pressure-change when a given P.D. is applied.

(6) *Influence of the velocity of sliding.*—As in the case of metal-metal contacts, the velocity of sliding makes very little difference to the pressure-change accompanying the application of a steady P.D.

Brass-agate was, however, exceptional in this respect (Fig. 23). At low voltages there was a decided tendency for the pressure-change to decrease as the speed increased, but at 200 volts this was negligible.

As regards the resistance, the velocity of sliding had no influence until the surfaces were brought to rest, when it gradually fell to a lower average value, taking about half a minute to reach its minimum.

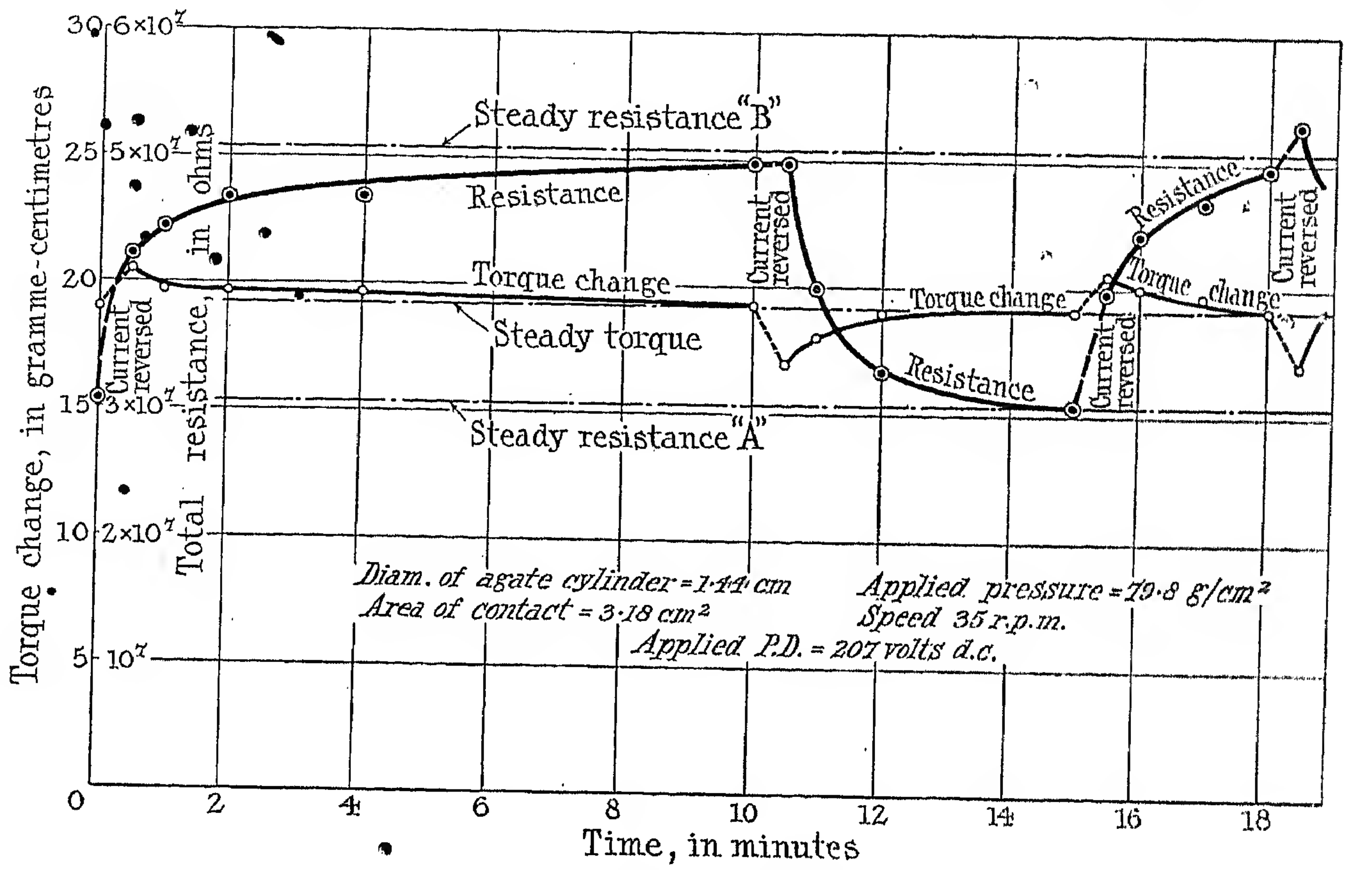

FIG. 22.—Variation of torque and resistance with time of application of P.D. between brass and agate, as measured by steelyard apparatus.

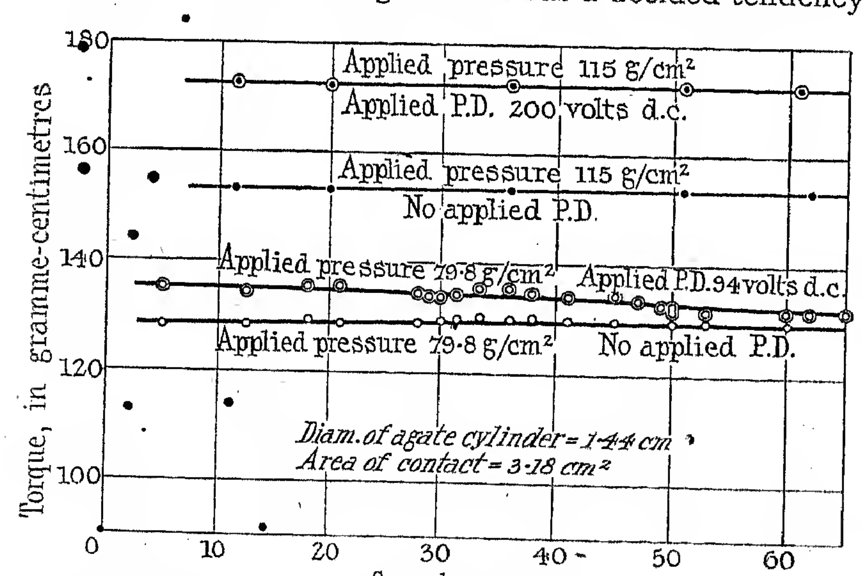

FIG. 23.—Variation of torque with speed, for brass-agate, as measured by steelyard apparatus.

Some experimental figures were taken for silver-lithographic stone and wrought iron-lithographic stone, and are given in Fig. 24. It will be observed that the change in resistance due to motion gets smaller as the applied P.D. is increased, exactly in the same way as for good conductors.

(7) *Comparison between the effects of alternating and direct currents.*—In order to ensure comparative conditions, alternating- and direct-current P.D.'s of the same value, as indicated by an electrostatic voltmeter, were applied alternately to a given contact. The torque-changes in each case were observed, but the instruments available were only suitable for measuring the direct-current resistance.

The results for brass-agate and brass-lithographic stone are given in Figs. 19 and 21. They are very similar to those obtained for wrought iron-wrought iron. The alternating P.D. caused the brake blocks to vibrate on the cylinder.

Some more precise information about the wave-form of the alternating-current supply was obtained in these tests. An oscillograph was used to record the E.M.F. curve at several different R.M.S. voltages (Fig. 25). With the aid of a planimeter the "form factor" was deduced in each case. It appears that the higher the R.M.S. voltage the smaller is this ratio.

(8) *Influence of body and contact resistances.*—Two thicknesses of celluloid were tested in the torsion apparatus under the same conditions. The results are shown in Fig. 17. Unfortunately, the samples must have been rather different in composition, because the total resistance was less for the thick piece.

With certain contacts, the application of P.D.'s up

to 550 volts produced no measurable change in the friction torque. This applied to the following cases :—

(*a*) *Copper-glass* (0·28 *cm thick*).
Torsion apparatus ($\frac{1}{16}$ in. diam. suspension) calibration 24·4 gramme-cm per degree.
Outside diam. of copper ring = 10·18 cm.
Inside diam. of copper ring = 7·6 cm.
Area = 36 cm^2.

(*b*) *Copper-ebonite* (0·22 *cm thick*).
Torsion apparatus ($\frac{1}{16}$ in. diam. suspension) calibration 24·4 gramme-cm per degree.
Outside diam. of copper ring = 10·18 cm.
Inside diam. of copper ring = 7·6 cm.
Area = 36 cm^2.

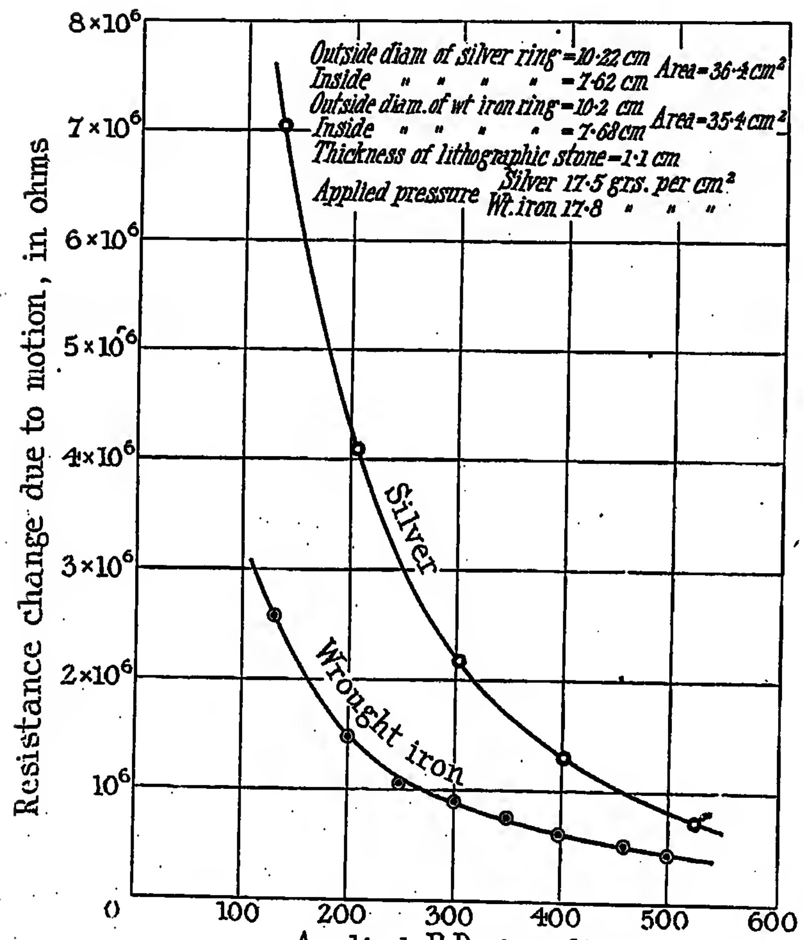

FIG. 24.—Change in resistance due to motion, with various applied voltages, as measured by torsion apparatus.

(*c*) *Copper-micanite* (0·2 *cm thick*).
Torsion apparatus ($\frac{1}{16}$ in. diam. suspension) calibration 24·4 gramme-cm per degree.
Outside diam. of copper ring = 10·18 cm.
Inside diam. of copper ring = 7·6 cm.
Area = 36 cm^2.

In the last case, (*c*), the contact was not very good, but sufficient to indicate any appreciable changes.

THEORY.

(1) *Pressure-changes and their relation to the contact resistance.*—When dealing with semi-conductors the analysis of the results is much simpler. The "stiction" effect persists over the whole range of currents considered. The application of a steady P.D. does not alter the coefficient of friction but merely adds to the applied pressure.

Our observations on semi-conductor contacts give very substantial support to the view that the "stiction" has its origin in electrostatic forces acting between the two surfaces. The currents employed were usually of the order of milliamperes, so that according to our theory any repulsion effect is quite negligible. The

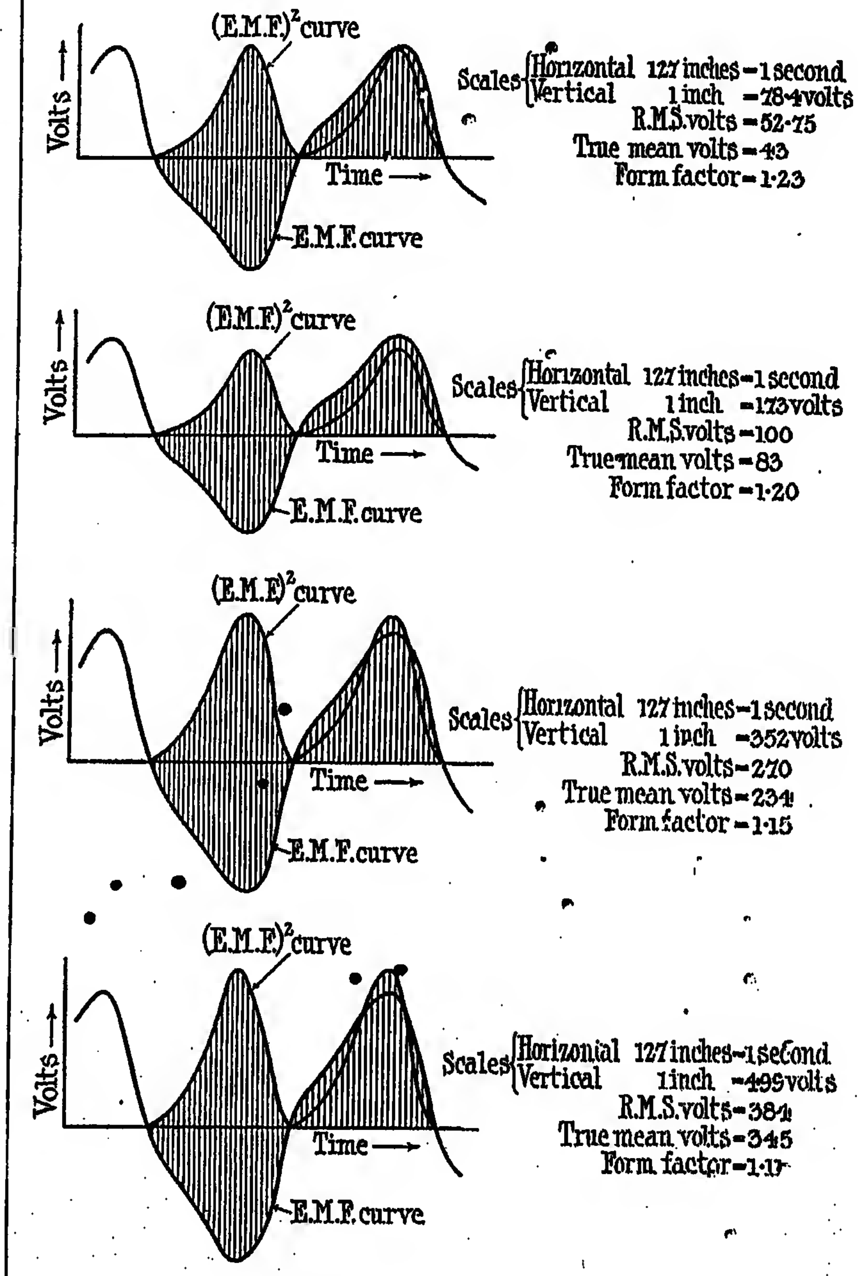

FIG. 25.—Oscillograph curves.

curves show that the rate of increase of pressure with applied potential generally begins to fall off about 350 to 400 volts. The total resistance of the circuit also drops rapidly as the terminal P.D. is increased. If we may assume that the body of the conductors follows Ohm's law, this conductivity change must occur at the two contacts with the semi-conductor. We conclude that the reduced stiction at the higher applied voltages is due to the decrease in the interface P.D. by reason of the coherer action. Although the current increases, the potential between the sliding surfaces becomes a smaller proportion of that applied to the terminals of the apparatus. If the contact was wet, the friction remained unaltered by the passage of a current, and the total resistance of the circuit was much lower. These are all significant facts. In most cases the

friction was greatest when the resistance had reached a maximum, but the brass-agate contact was an exception. In this instance the steady pressure-change corresponding to a certain applied P.D. was unaffected by the direction of the current, suggesting that the drop across the interface finally attained the same value. This is consistent with the supposition that the interface P.D. is partly determined by the magnitude of the current passing.

(2) *Comparison between different areas of contact.*—The comparison between different areas of contact carried out for copper-celluloid leaves little room for doubt that the "stiction" is directly proportional to the extent of the surface. The same sample of celluloid was used throughout the test.

(3) *Comparison between the effects of alternating and direct currents.*—Figs. 19 and 21 show the relative pressure-changes corresponding to various R.M.S. applied voltages. The "form factor" of the alternating E.M.F. wave is given in Fig. 25. Taking the true mean or time average of the applied P.D.'s, we see that the "stiction" is practically the same whether the supply be steady or varying, again confirming the view that the effect is due to electrostatic forces.

(4) *The significance of body and contact resistance.*—The friction between metal and either glass, ebonite, or micanite, was not measurably altered by a current passing across the junction. We conclude, therefore, that the body resistance of these semi-conductors, or perhaps more appropriately dielectrics, is large compared with the resistance of the contact. Not more than a fraction of a volt could have been absorbed at the interface without being detected.

The condition for stiction is simply that the insulating property of the semi-conductor is furnished by the contact rather than by the mass of the material. Some experiments which we shall describe on the direct-current conductivity of lithographic stone and slate, as measured between mercury electrodes, indicate the importance of the contact in these cases.

As far as we are aware, no attempt has been made to distinguish between body and contact resistances. It seems to have been taken for granted that the transition resistance from electrode to dielectric was always relatively negligible, particularly if the connection was made with mercury. This is far from the truth in many cases. Some suggestive experimental results are given by Addenbrooke * for the direct-current resistivity of celluloid as measured between mercury electrodes. Samples of different thickness were tested under similar conditions. The figures are reproduced in Table 3.

It is clear that the total resistance per unit area must have been very nearly the same for all three samples, both when ordinarily dry and specially dried. To us the conclusion is irresistible that a large proportion of the resistance must have been in the mercury contact, but Addenbrooke attributes the apparent irregularity to variations in the amount of absorbed moisture.

It is significant that merely to wet the metal-lithographic stone surfaces employed in the friction tests reduced the effective resistance of the circuit to about a quarter of the original value.

This somewhat remarkable correlation of facts can have only one interpretation : many substances must rely largely on the contacts for their insulating properties. Under standardized conditions, the magnitude of the pressure-increase produced at the junction of a semi-conductor and a metal conducting a current, is an excellent basis for comparing the real value of different substances as insulators. By testing various thicknesses of a particular sample of semi-conductor the body and contact resistances are easily separated.

Such an investigation is not confined to direct current. Some observations with high-frequency currents might lead to very important results, and supply us with more information about the variation in the apparent conductivity of a dielectric with frequency. It is not unlikely that the change really occurs in the contacts.

To distinguish properly between body and contact resistances it would be necessary to employ mercury

TABLE 3.

Thickness	Specific resistance	
	Room dryness	Dried
mm	ohms per cm cube	ohms per cm cube
0·62	$1 \cdot 7 \times 10^{10}$	—
0·4	$3 \cdot 2 \times 10^{10}$	$2 \cdot 9 \times 10^{12}$
0·23	$5 \cdot 7 \times 10^{10}$	$4 \cdot 4 \times 10^{12}$

electrodes on both sides of the semi-conductor, and to do away with the necessity for grinding the contact. A simple and satisfactory arrangement might be made by passing a stream of mercury under pressure through a pipe of the semi-conductor immersed in mercury and measuring the fall in the head over a definite length, with and without a P.D. applied between the inside and outside electrodes. Alternatively an apparatus of the form used by Heyl for metal-metal contacts might give good results. In classifying different materials, allowance would have to be made for the increased resistance of the contacts due to relative motion, but this should not be a difficult matter.

Our experiments are sufficient to show that such materials as slate, red fibre, paxolin and celluloid can only be classed as dielectrics in virtue of their high contact resistance, and that the true body conductivity of these semi-conductors cannot be measured with mercury electrodes.

ELECTRICAL EFFECTS AT STATIONARY CONTACTS.

EXPERIMENTAL WORK.

(1) *Transition resistances of metal-metal contacts.*—In order to estimate the transition resistance at standstill of the annular metal contacts employed

* *Journal I.E.E.*, 1919, vol. 57, "Institution Notes," p. (13); and *Proceedings of the Physical Society of London*, 1915, vol. 27, p. 291.

in the friction tests, the apparatus shown in Fig. 26 was employed.

Electrical connection was made with the upper and lower surfaces of the rings by means of ebonite-mercury troughs. In this way the nature and area of the contact were rendered definite, so that any given conditions could be repeated. Great care was taken to clean the surfaces.

By a process of elimination, figures were obtained

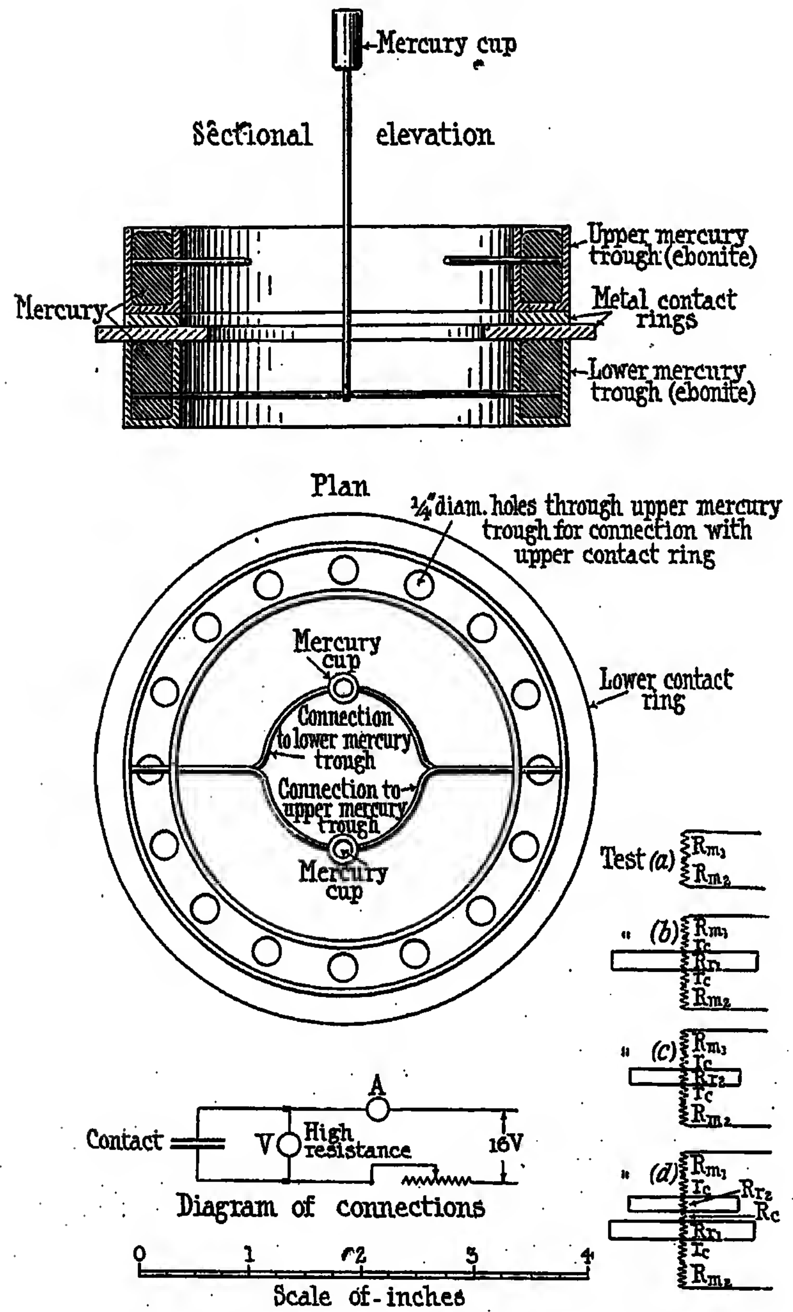

FIG. 26.—Apparatus for measuring the resistance of metal-to-metal contacts.

for the actual interface resistances, but these were not of much value because the contact between mercury and ring was supposed perfect.

The experiments showed, however, that the mercury contacts very nearly followed Ohm's law, so that an indication was given of the interface resistance characteristics. These correspond in a rather remarkable manner to the friction-changes associated with the passage of a current across a sliding metal-metal contact.

When the rings had been ground together, washed and dried in the usual way, the initial resistance of the circuit, test (*d*), as measured by a small current, was generally very high. As the current was increased, the P.D. also increased simultaneously in direct proportion, but periodically it fell suddenly to lower values. Sometimes the deviation from Ohm's law took a second or two to operate. This was not due to the inertia of the voltmeter needle or lack of damping.

Usually one of the resistance-changes was more marked than the others. At a certain critical current the P.D. might fall to half its original value. After the current had been increased to about 30 or 40 amperes the conditions became more or less stable, although there were always minor fluctuations, which continued when the applied P.D. was maintained constant. If now the experiment was repeated, the resistance for small currents was found to be only a little greater than that for large currents, and this condition was practically unaltered by further tests, and therefore corresponded to the "final state."

After washing and drying the surfaces again, the "initial state" was invariably restored. Merely to re-dry them produced no effect. If the contact was left untouched in the final state for some hours, the initial state was never completely re-established, although there was always a tendency to recovery. Continually tapping the rings produced a semi-sensitive condition.

(2) *The direct-current conductivity of lithographic stone and slate.*—Samples of the semi-conductor were cut in the form of a cylinder and were tested between mercury electrodes as shown in Fig. 27. The current corresponding to a steady applied P.D. of about 500 volts was observed at intervals after the circuit was

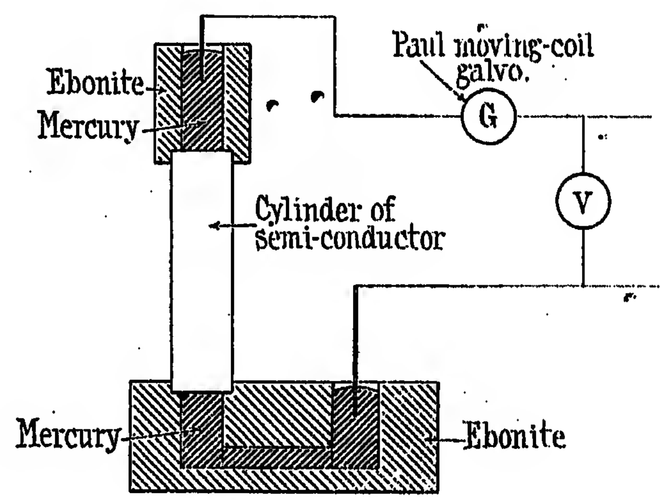

FIG. 27.—Arrangement of direct-current conductivity test.

closed. When the current had become approximately constant the P.D. was reversed and the observations were repeated.

About a dozen such tests were made on each of three cylinders of the same material, having a diameter of 1·05 cm and lengths of 0·55 cm, 2·6 cm and 10·8 cm respectively. No two series of readings for a given specimen were exactly alike, but typical curves are represented in Fig. 28 for lithographic stone and in Fig. 29 for slate. The figures for lithographic stone were by far the more consistent, and the "residual charge," which sometimes has an important influence,

was comparatively small in this case, even after a prolonged application of the P.D. The magnitude of the "residual charge" was estimated by the value of the current produced when the system was short-circuited through the galvanometer.

been in the body of the material, according to the ordinary laws of conduction we should have expected the shortest cylinder to have a conductivity about 20 times as large as that of the longest.

Whatever allowance be made for the influence of

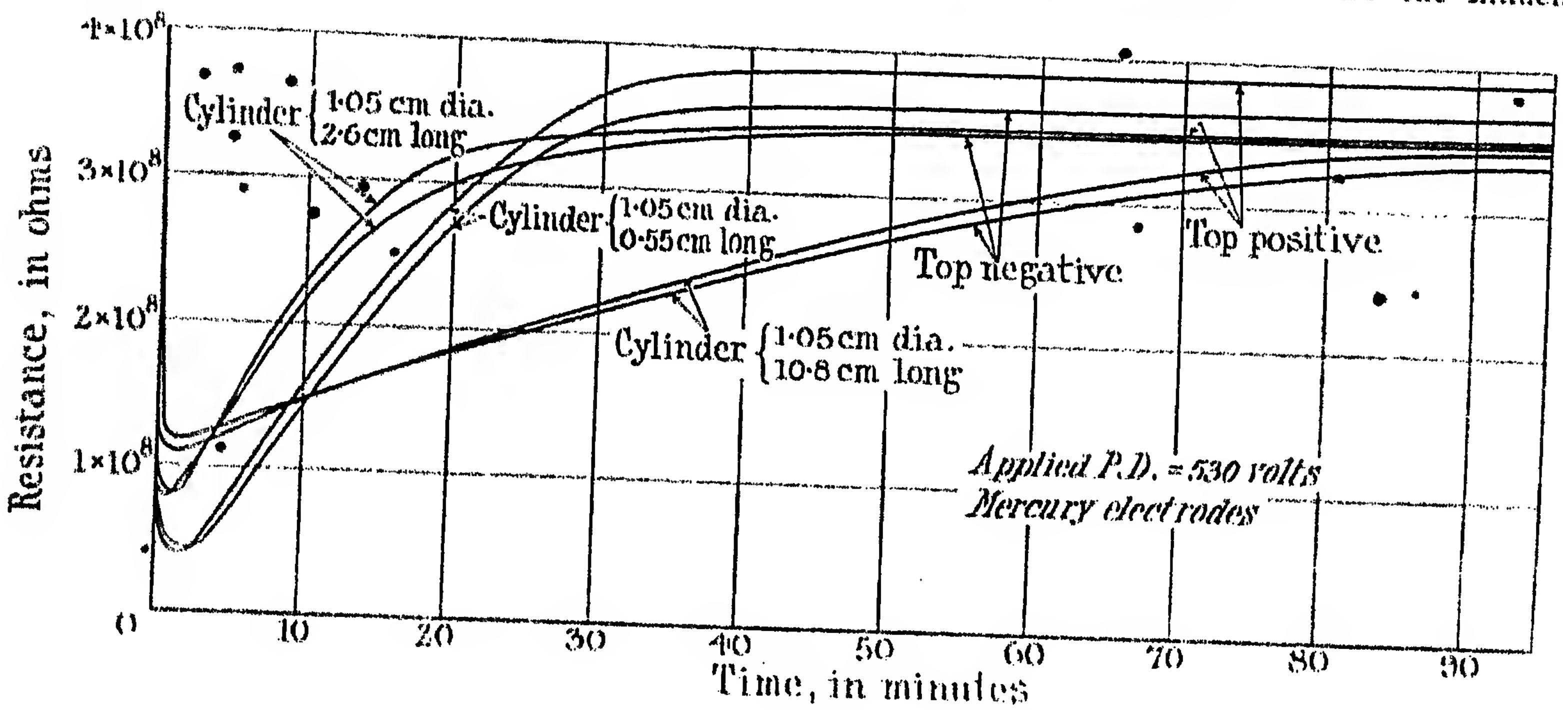

FIG. 28.—Direct-current conductivity of lithographic stone.

The three different cylinders were cut from the same piece of material in both cases, and care was taken to subject them all to the same treatment. After washing with soap and water they were dried in a

the residual charge, variations in the amount of moisture present, surface leakage, etc., we cannot get away from the conclusion that by far the greater part of the resistance must be in the contacts between

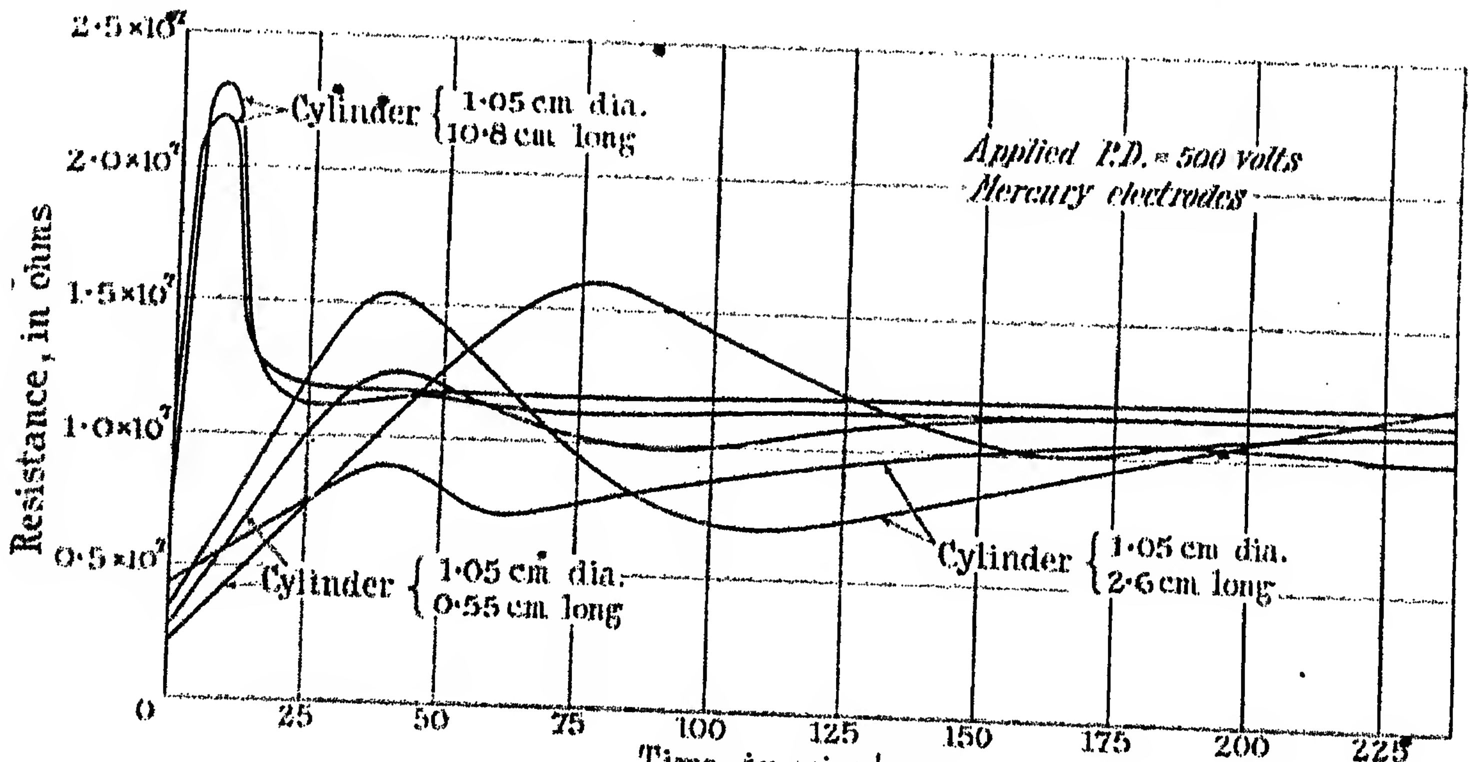

FIG. 29.—Direct-current conductivity of slate.

stream of hot air for about an hour, and then allowed to cool.

It is remarkable that the final apparent resistance of all three cylinders was about the same, both for lithographic stone and for slate. Had the resistance

mercury and semi-conductor. When two cylinders were connected in parallel the effective resistance was about halved, and when in series about doubled.

The arrangement behaved much in the same way as a leaky condenser. There was always an initial

rush of current when the P.D. was first applied. As the system became charged the current dropped, finally reaching a more or less steady value.

Absorption involves the establishment of a back E.M.F., which increases with the time of application of the external P.D. and adds to the apparent resistance of the circuit. By reversing the direction of the external P.D. the absorption E.M.F. is destroyed in a few minutes, and then it gradually builds up in the opposite direction.

In the case of slate the resistance reached a maximum soon after switching on, and at this point the residual charge was found to change its sign. There is little doubt that the curious variations in the conductivity of slate were largely due to the effect of the residual charge.

The initial rush of current was always greatest with

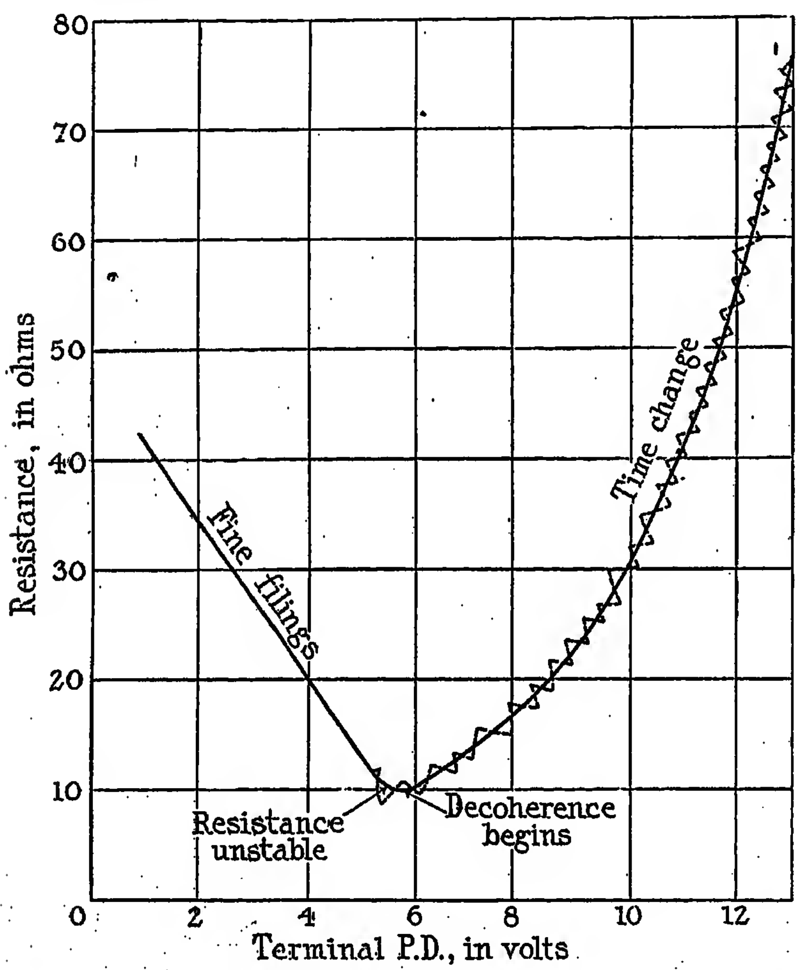

FIG. 30.—D.C. resistance characteristic of copper-filings coherer.

Copper electrodes; fine filings.

the shortest cylinder, and the characteristic resistance instability of solid imperfect contacts was not very apparent in these experiments.

(3) *Coherer characteristics.*

(*a*) *Metal filings.*—Only comparatively small voltages and currents are required to produce the so-called coherence phenomenon, but in the following experiments as much as 13 volts was applied to the terminals of some of the coherers tested, and currents up to 10 amperes passed through them.

The apparatus consisted of a glass tube about ¼ in. internal diameter having metal plugs in the ends, enclosing loosely packed filings. The plugs were connected to insulated terminals and were always made of the same metal as the filings.

It is unfortunate that in a great many researches carried out on this subject the active materials employed have been a mixture of two or more different substances. We must bear in mind that the contacts between plug and filings also have a share in producing the observed resistance-changes, and may in certain cases have a controlling influence.

Most of the common metals and graphite were tested in the manner described, the resistance being deduced from measurements of the terminal P.D. corresponding to a given current. A high-resistance voltmeter was used, so that it did not by-pass any appreciable current.

Typical curves for silver and copper are shown in Figs. 30 and 31. As the P.D. is increased, the resistance falls rapidly at first and then tends towards a minimum value. This stage corresponds to what has been called

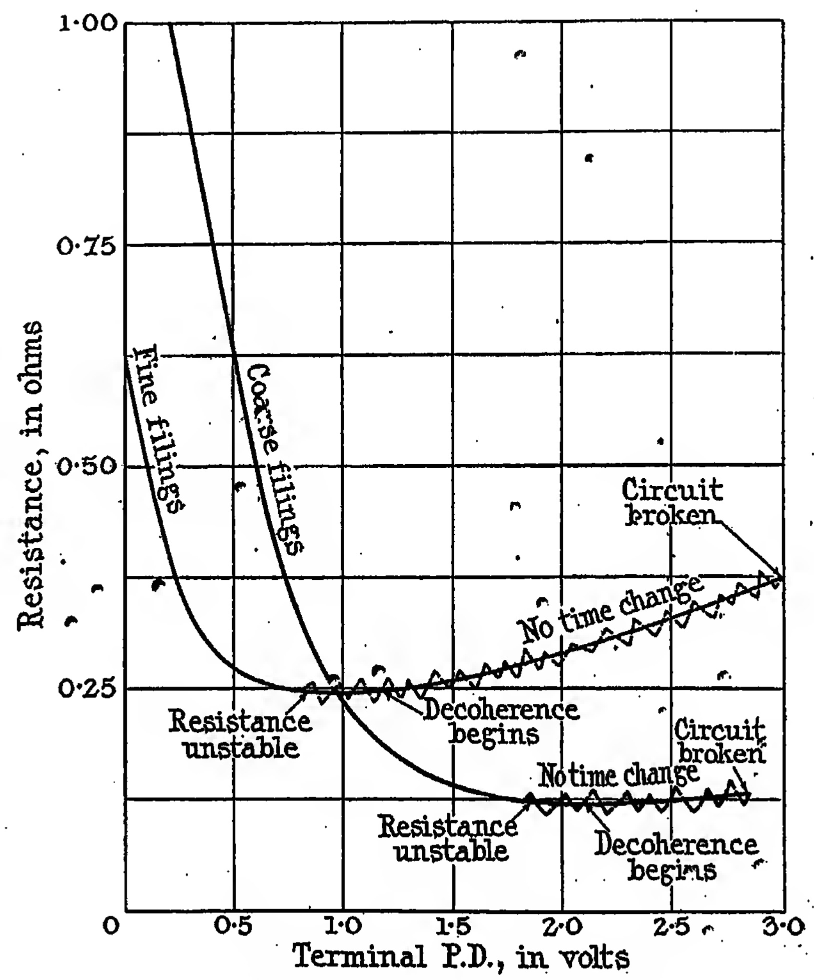

FIG. 31.—D.C. resistance characteristic of silver-filings coherer.

Silver electrodes.

"coherence," and is the normal working range of the commercial instrument. Further increase in the applied potential produces a sudden, very marked instability of the resistance, the average value of which begins to get larger again. In the case of copper, the filings had obviously become warm by this time and were beginning to discolour. The resistance-change became automatic, the current slowly falling and the P.D. rising as the oxidation of the particles spread from the positive to the negative electrode. This process continued for some hours until finally the conditions became very nearly steady.

If, however, during the time-change the external resistance of the circuit was suddenly altered so as to increase the current, there was generally a simultane-

ous complete rupture between the particles in the tube, followed by a spark. This effect occurred more easily when the filings were loosely packed.

The gradual decoherence action which proceeded automatically was found to be independent of the direction of the current and took place in a series of little jumps.

After the filings had become well oxidized the initial conditions were not easily restored by shaking the tube, especially if a P.D. was maintained across the terminals. But if continuity was successfully re-established, the first stage in the resistance-changes was always repeated. When the minimum value of the resistance was reached it became exceedingly unstable, and a further increase in the applied P.D. caused an interruption in the circuit.

The characteristic curve for silver is very much the same, except that the time-change does not appear in this case. The tube first of all coheres and then decoheres, completing the process with a sudden rupture between the particles. As the test proceeded there was very little discoloration of the active material and the temperature-rise was comparatively small.

The size of the filings had a noticeable influence. With small particles loosely aggregated, the minimum resistance is reached with a smaller applied P.D., and the decoherence can be followed more easily without causing a premature break in the circuit. An examination of the filings after the test showed that there could not have been any welding in the ordinary sense of the word. They fell apart immediately if touched.

Any sudden changes in the applied P.D. during the final stages of the resistance-changes invariably produced a simultaneous rupture in the circuit. The conditions were anything but stable during this phase. The ammeter and voltmeter needles were constantly wobbling up and down in opposite directions, whilst the increase in resistance as the terminal P.D. was raised was accompanied by a series of sparks among the filings.

After the filings had been used once, the sulphide film formed on their surface appeared to increase the sensitivity of the arrangement, so that the cycle of resistance-changes could be repeated with considerably smaller currents.

A number of other metals were tested in the same way and always with the same general results. Lead, tin, aluminium and zinc all interrupted the circuit soon after the coherence was complete. In one case there was a small time-change, but it was not easily followed.

The characteristic curves for copper and silver were selected as being fairly representative of the non-magnetic metals.

Nickel and wrought iron only interrupted the circuit when sufficient current was passed to make the filings red hot. If finely-divided wrought iron was placed between brass plugs the system behaved in the ordinary way. Judging from the position of the sparks, the rupture occurred between the filings and the electrode.

A tube containing powdered graphite was found to cohere slightly, but could not be induced to decohere.

(*b*) *Lead peroxide.*—Fig. 32 represents a typical direct-current characteristic for compressed lead peroxide contained between metallic lead electrodes. In practically every detail it corresponds exactly to that obtained for copper.

THEORY.

(1) *Coherence and decoherence.*—Although the resistance-changes at an imperfect contact may, in many cases, be largely due to a readjustment of its parts by the interface forces, there must also be other considerations involved.

A circuit including two rigid metal plates pressed together gives a small deviation from Ohm's law, as our experiments on stationary ring contacts showed. On the other hand, a mercury connection has a relatively constant resistance. We conclude that the gaps between the surfaces are chiefly responsible for the change. Our hypothesis regarding the action of the interface film at once offers an explanation. For a given P.D. the gaps assisting in the conduction of electricity will all be within a certain maximum length, the selection being made according to the potential gradient. As the applied P.D. is increased, the ionization of the gas between the surfaces will be extended and, consequently, the effective resistance of the contact will be reduced. The change will actually occur in little jumps, but the "critical" potentials may be so close together that the effect appears gradual. The fit of the surfaces is the determining factor, and if there is one particularly pronounced drop in the resistance it simply means that a large number of gaps have become active together. When the two parts of the contact are in relative motion the spacing is averaged, and consequently there is always one very marked critical P.D., which we have seen corresponds to the transition from the initial to the final state. Moreover, the small interval of time required to effect the increase in conductivity is consistent with the mechanism we are describing.

As soon as a gap becomes ionized it also becomes susceptible to electromagnetic striction, which will produce mechanical forces tending to separate the surfaces. The electrostatic attraction will temporarily cease to operate on account of the relatively low interface resistance. But if the parts of the contact are free to move they will do so in such a manner that the distance between them is increased and the conductivity of the system correspondingly reduced. At the same time the contraction of the conducting veins due to the pinch effect will become more pronounced as the current rises, so that their effective resistance will also become larger by this means.

The various effects we have described can be more or less followed from the coherer characteristics (Figs. 30 to 32). The decoherence in the cases of copper and lead peroxide must have been largely due to a chemical change in the nature of the surface, produced by heating. As we should expect, the accompanying resistance-change was automatic. But the silver-filings coherer gave very similar results without any appreciable suggestion that they were complicated by an alteration in the state of the surfaces. Moreover, all the metals tested ruptured the circuit when the current was sufficiently increased or the external resistance suddenly changed. The effect worked more easily when the

filings were loosely packed, and sometimes occurred in stages if the particles were small. All these observations might have been predicted from our theory. The thickening and extension of the interface film would also assist in the concentration of the current stream-lines and the striction would gradually interrupt the various parallel paths through the tube. The action is obviously cumulative, because a break in one contact means that more current has to pass through the others, and ultimately complete discontinuity will be established.

That the coherence of iron and nickel is partly a magnetic effect was proved by our experiments. The fact that iron loses its high permeability at about 800° C.,

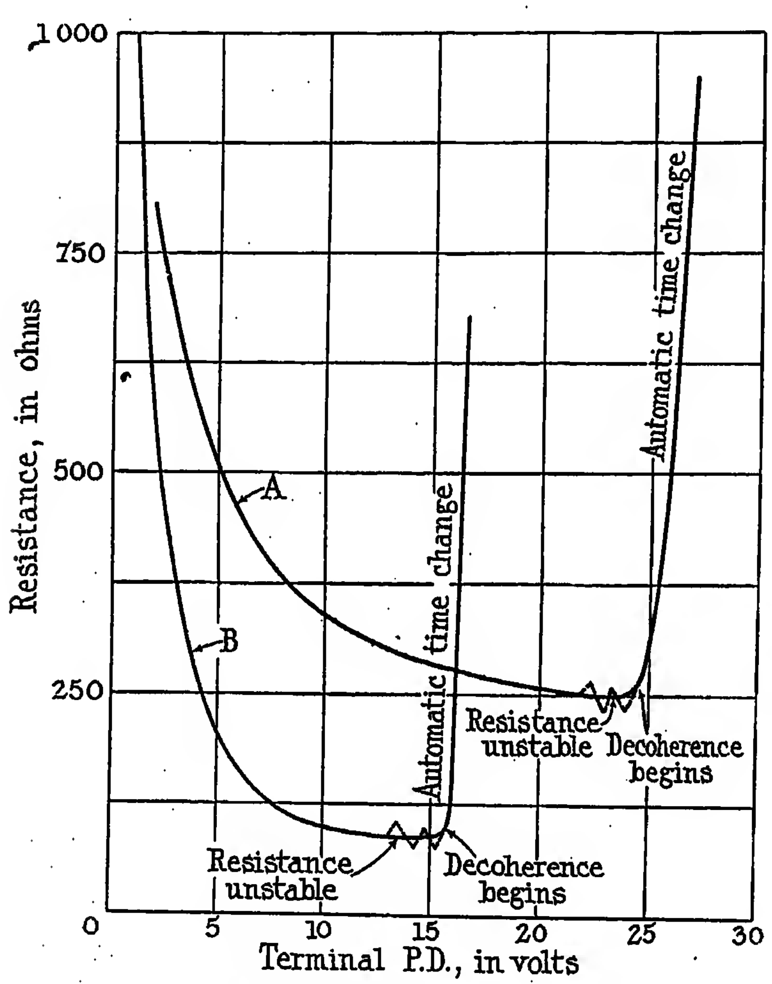

FIG. 32.—D.C. resistance characteristic of lead-peroxide coherer.

Metallic lead electrodes.

and nickel at about 370° C., and that an interruption in the circuit through tubes containing filings of these metals could only be brought about at red heat, is very significant. Again, a mixture of iron and brass decohered immediately.

(2) *The instability of the resistance of an imperfect contact.*—We have remarked that in all the imperfect contacts with which we have been concerned, except perhaps where mercury forms one of the electrodes, the interface resistance manifests a curious instability, which is quite independent of mechanical vibration.

If we consider once again the operation of the film between the surfaces, we see that the magnitude of the current conducted by the gaps may vary even when the applied P.D. remains constant. The area of active surface depends upon the voltage-drop across the contact. An extension of the number of conducting gaps is simultaneously accompanied by a reduction in the interface P.D., because the total current must remain approximately constant. Consequently, such a change will be very quickly arrested, and then continued again as soon as the contact resistance has risen sufficiently. It is clear that the conductivity of the junction, and the voltage across it, are interdependent, producing very unstable conditions. The striction of the conducting veins of mobile conductor in the interfaces may also exert an influence. A small increase in current will tend to reduce the section of these veins and therefore increase their effective resistance.

Correlation of Facts and a General Theory of Imperfect Contacts.

When reading through the literature of this subject, one notices an unfortunate tendency to keep the various theories in watertight compartments. Where we are concerned with processes of such an involved nature, we cannot afford to limit our attention to one particular point of view.

Our experiments have shown that the mechanical pressure at an imperfect contact of good conductors is first increased and then decreased as the applied P.D. is raised. The conductivity of the system has been proved to follow a similar cycle of changes, and is known to be exceedingly sensitive to the interface forces. It follows that if the active material (including the interface mobile conductor) is capable of readjustment under the influence of small alterations in these forces, the principal characteristics at once become more or less intelligible. We have already discussed in detail the influence of the interface film. Here it will be sufficient to point out that coherence and decoherence would be impossible without it, and that when the solid boundaries are incapable of displacement the mobile conductor between them alone determines the conductivity changes by variations in its distribution and the degree of ionization.

Although the resistance of a sliding contact is always greater than that of a similar stationary one, the evidence suggests that the same considerations apply in both cases.

Conclusion.

In conclusion the author wishes to express his sincere thanks to Prof. J. A. Fleming, M.A., D.Sc., F.R.S., for placing the resources of the Laboratory at his disposal and for advice during the course of the work; and to the Department of Scientific and Industrial Research for financial assistance.

APPENDIX 1.

The paper recently published by Messrs. Johnsen and Rahbek * dealing with the adhesion set up between a metal plate and a semi-conductor with which it is in close contact, contains several statements which are apparently in conflict with the results of our observations on this subject.

* *Journal I.E.E.*, 1923, vol. 61, p. 713.

In the first place, it is asserted that the contact resistance, which plays so important a part in the "stiction" phenomenon, is absent with mercury electrodes. Our experiments on the direct-current conductivity of lithographic stone and slate suggest that this is extremely unlikely, but in order to clear up the matter we have carried out the following tests.

A disc of polished lithographic stone was suspended horizontally by a flexible wire from one end of the arm of a balance so that it just touched the surface of a pool of mercury (see Fig. 33). The wire was electrically connected to the stone, in some cases by a piece of tinfoil spread over it, and in others by a layer of mercury enclosed in wax. On account of the exclusion of the atmosphere at the contact and the cohesion operating across the interface, about 12 to 13 grammes per square inch was required to raise the semi-conductor from the mercury. When, however, a P.D. was applied across the contact the force necessary to separate the

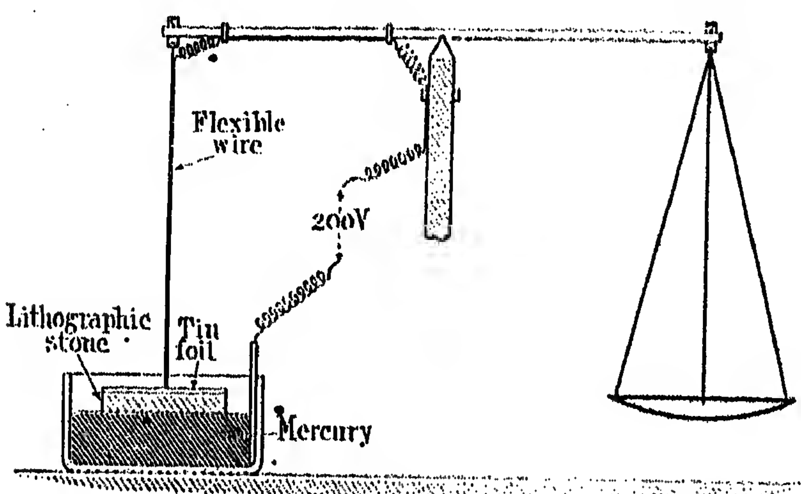

FIG. 33.—Apparatus for observing the electro-adhesion at a mercury-semi-conductor contact.

two parts was considerably increased. With a lithographic stone disc of about ¾ square inch area, and 200 volts (a.c.) supply, about 2 to 3½ grammes extra weight had to be added to the scale pan to upset the equilibrium. If, say, 2 grammes were added to the scale pan when the current was on, as soon as it was switched off the lithographic stone disc came right away from the mercury. Moreover, if the disc was tilted slightly so that it only made contact at one corner, the application of the P.D. immediately brought the two surfaces together over the whole area. This process could be observed quite easily. Great care was taken to secure perfectly clean mercury, and the lithographic stone was washed and dried before using. With a very thin film of petroleum oil covering the mercury surface the "initial pressure" fell to about 7 or 8 grammes per square inch whilst the superimposed stiction effect accompanying the application of a P.D. of 200 volts increased to 3 or 3½ grammes for an area of ¾ square inch. The results were exactly the same whether the connection to the upper surface of the semi-conductor was made with tinfoil or mercury.

Some tests on xylonite and slate in contact with clean mercury gave similar observations. In the case of xylonite the average "initial pressure" was 10 grammes per square inch, and the average additional adhesion effect due to 200 volts was 0·2 gramme per square inch. For slate an "initial pressure" of 8 grammes per square inch was increased to 10 grammes per square inch when the current was passing.

These facts show definitely that a very considerable "stiction" effect exists at a contact between a semi-conductor and mercury. The phenomenon is by no means confined to the case of solid electrodes. Since the adhesion is electrostatic in origin, it follows that the resistance of the interface film between the mercury and the semi-conductor is far from negligible; in fact it must be a large proportion of the total resistance of the circuit. It is significant that the nature of the contact on the upper side of the semi-conductor made no observable difference to the increase in the adhesion due to an applied P.D.

We should be interested to know how Messrs. Johnsen and Rahbek measured the distribution of potential over a circuit including a metal plate in contact with a piece of lithographic stone, curves for which are given in their paper.

It would appear that it is only possible to secure a really low-resistance contact when the liquid electrode wets the surface of the semi-conductor, and then the junction ceases to be what we call "imperfect." The supposition that mercury exactly follows the contour of the semi-conductor and thus eliminates air-gaps, is a fallacy.

Our experiments on the "slipping" effect observed in certain types of contact show that this is generally due to a reduction in the pressure between the surfaces, and not to a change in the coefficient of friction. Exceptions to this rule were only found in the cases of copper-graphite and graphite-graphite, and even in these instances the change was principally in the forces across the interface. The effect which altered the coefficient of friction did not operate simultaneously with the application of the current. The Edison electromotograph could not have worked by the part of the "slipping" action with which any appreciable time-lag is associated, and therefore, unlike Messrs. Johnsen and Rahbek, we conclude that the main function of the current was to produce a reduction in the mechanical pressure between the surfaces. The theory of electrolytic dissociation of the moisture at the interface receives little support from the facts. On the other hand we venture to believe that our hypothesis, that the "pinch effect" is responsible for the phenomenon, explains all the experimental observations, and at the same time satisfactorily accounts for the rapidity of the friction-changes.

APPENDIX 2.

The electrostatic forces which, we have shown, are produced by the application of a potential difference between a liquid metal, such as mercury, and a semi-conductor in contact with it, have been utilized by us in several instruments.*

* Patents have been applied for.

A telephone receiver can be made by simply floating a thin disc of lithographic stone, having its under side slightly concave, upon a pool of mercury so that only part of the surface is normally in contact. Electrical connection is made to the upper side of the stone disc by tinfoil cemented to it. The application of a varying potential difference between the tinfoil and the mercury causes a corresponding vibration of the semi-conductor. The attraction set up at the interface by the passage of the electric current across it pulls the semi-conductor periodically into more intimate contact with the mercury. The sound is produced either by the direct action of the vibrating disc on the surrounding air, or by the compression and rarefaction of the air partially enclosed between the mercury and the under side of the semi-conductor, a small hole, through which the air is forced in and out, being provided in the centre of the disc.

A very simple galvanometer for an oscillograph can be made by employing a piece of semi-conductor oscillating on the surface of mercury, so that its motion corresponds to the wave-form of the applied E.M.F.

APPENDIX 3.

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DIRECTIONS FOR THE STUDY OF VARNISH-PAPER AND VARNISH-FABRIC BOARDS AND TUBES.

[REPORT (REF. A/S6) RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

CONTENTS.

PREFACE.

For some time the Association has been engaged in the study of varnish-paper and varnish-fabric boards and tubes. In the past no standard method of testing materials of this class has been recognized, and therefore methods of test were developed. As the result of the investigations which have been carried out the tests described in this Specification are recommended for the purpose of ascertaining the electrical, mechanical and chemical characteristics of varnish-paper and varnish-fabric boards and tubes.

The tests contained in Section II of the Specification are essentially of a thorough research nature, whilst the abridged tests given in the Schedule are intended for use when a complete investigation of all the characteristics of the material is not required.

The Director of the Electrical Research Association will value comments and criticism from those who have occasion to use any of the tests given in this Specification.

I. DEFINITIONS AND CLASSIFICATION.

(a) Definition of Varnish-paper and Varnish-fabric Boards and Tubes.

The term "Varnish-paper (Fabric) Board (Tube)" denotes a board (tube) made from superimposed layers of paper (fabric) treated with varnish.

(b) Classification of Varnish-paper and Varnish-fabric Boards and Tubes.

The following classes and grades are recognized:—

Class I. Synthetic Resin Varnish-paper and Varnish-fabric Boards and Tubes.

Grade A.—This includes synthetic resin varnish-paper (fabric) boards (tubes), the principal characteristics of which are low water absorption, high resistivity, and good machining properties. This class of material does not necessarily possess a high electric strength at high temperatures, and is generally used for radio work and electrical apparatus where the dielectric is not subjected to a high electric stress at a high temperature.

Grade B.—This includes synthetic resin varnish-paper (fabric) boards (tubes), the principal characteristic of which is a high electric strength at high temperatures. This grade, in general, has not as good machining properties as Grade A, and is generally used in electrical machinery where high electric strength is required at a high temperature, as, for example, in oil-immersed plant.

Grade C.—This includes synethetic resin varnish-paper (fabric) boards (tubes) made from an inorganic paper or fabric (such as asbestos). The principal characteristics of this material are its ability to withstand a high temperature without serious loss of mechanical properties. This grade in general has not as high an electric strength as either Grade A or Grade B, is more hygroscopic and of lower resistivity. Its machining properties, although sufficiently good to permit of its being drilled, sawn, etc., are not in general as good as those of Grade A or Grade B.

Class II. Natural Gum or Resin Varnish-paper and Varnish-fabric Boards and Tubes.

Grade A.—This includes natural gum or resin varnish-paper (fabric) boards (tubes) possessing relatively high electric strength, and able to withstand temperatures up to 95° C. without softening. This material is generally used for transformer insulation.

Grade B.—This includes natural gum or resin varnish-paper (fabric) boards (tubes) possessing relatively high electric strength and able to withstand temperatures

up to 70° C. without softening. This material is generally used where the temperature-rise is small.

NOTE. It is recognized that special materials are obtainable which do not fall into any of the grades given above, as, for instance, bitumen-paper board and linseed oil varnish-paper board.

(c) *Terminology.*

(i) The term "Longitudinal" denotes the direction parallel to that in which the material travelled during manufacture.

(ii) The term "Transverse" denotes the direction at right angles to that described in (i) above.

(iii) The term "Perpendicular" denotes the direction normal to the surface of the material.

NOTE.—When the material is built up of superimposed layers having the "grain" at right angles, there is no definite longitudinal or transverse direction.

II. METHODS OF TEST.

1. Conditioning of Specimens previous to Test.

(a) *Electrical Tests.*

The Electric Strength, Clause 3, the Resistivity, Clause 4, the Surface Resistivity, Clause 5, and the Internal Resistance, Clause 6, shall be determined for as many as possible of the following conditions:—

(i) "Normal" Condition
(ii) "Dry" Condition
(iii) "Damp" Condition
(iv) "Tropical" Condition
(v) "Recovered" Condition

See Technical Publication Ref. A/S2, Directions for Determining the Electric Strength of Fibrous Insulating Materials.

(b) *Mechanical and Physical Tests.*

Before determining the mechanical and physical characteristics as specified in the respective clauses, the specimens shall be dried at a temperature from 75° C. to 80° C. for 18 to 24 hours, except in the case of Class II, Grade B materials, the temperature for which shall be from 55° C. to 60° C. The test shall be conducted as soon as the temperature of the specimen has fallen to 20° C. (± 5° C.) except where otherwise specified.

(c) *Chemical Tests.*

The chemical tests shall be carried out on the material as received without conditioning.

2. Determination of Thickness.

The specimen shall be conditioned in accordance with Clause 1 (b) before the thickness is determined.

(a) *Boards.*

Measurements of thickness shall be made by means of a suitable micrometer at ten points equally spaced around the sides of the board. The maximum, minimum and mean values of the thickness shall be stated.

(b) *Tubes.*

The internal and external diameters of the tube shall be measured at each end, two measurements being made on diameters at right angles in each case. The measurements shall be made by means of a suitable micrometer. The maximum, minimum and mean values of the diameters shall be stated.

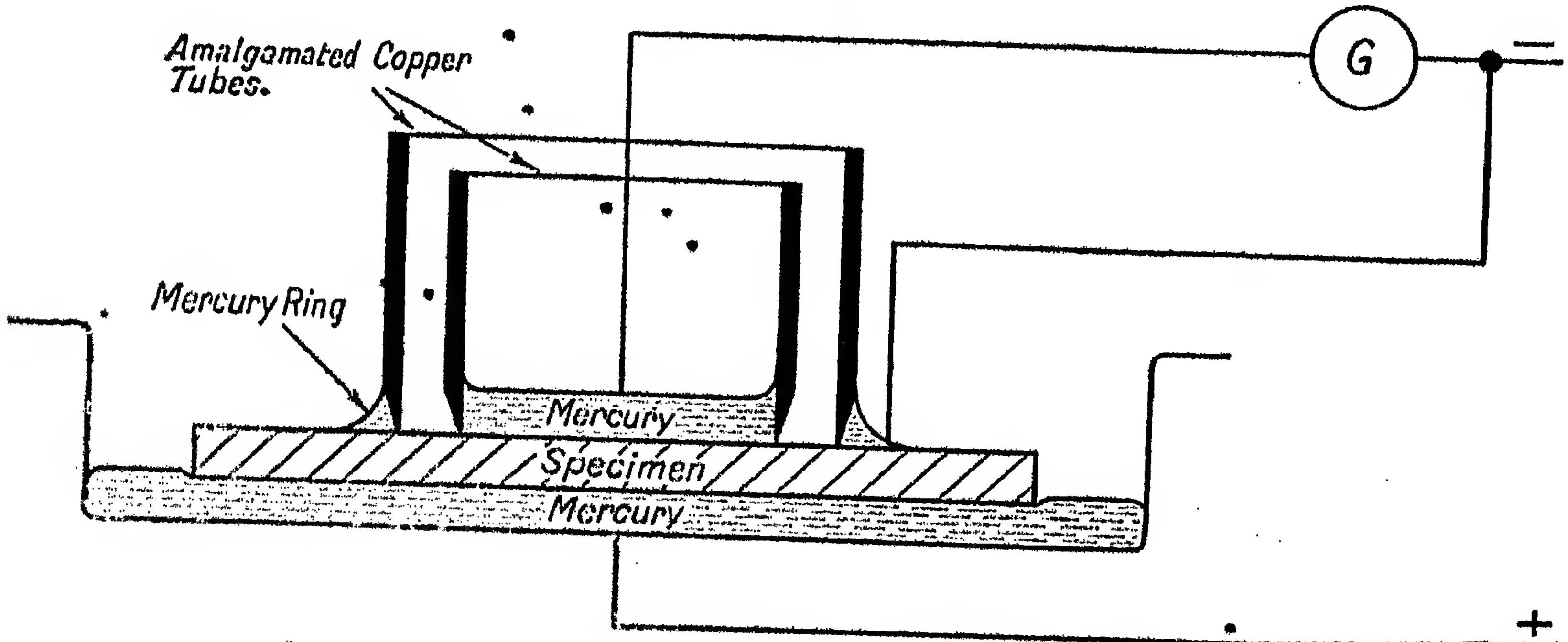


FIG. 1.—Diagrammatic Arrangement of Apparatus for Volume Resistivity Test.

3. Electric Strength.

The electric strength shall be determined in accordance with Technical Publication Ref. A/S2, Directions for Determining the Electric Strength of Fibrous Insulating Materials.

4. Resistivity.

The specimen shall be conditioned in accordance with Clause 1 (a) before the resistivity test is carried out

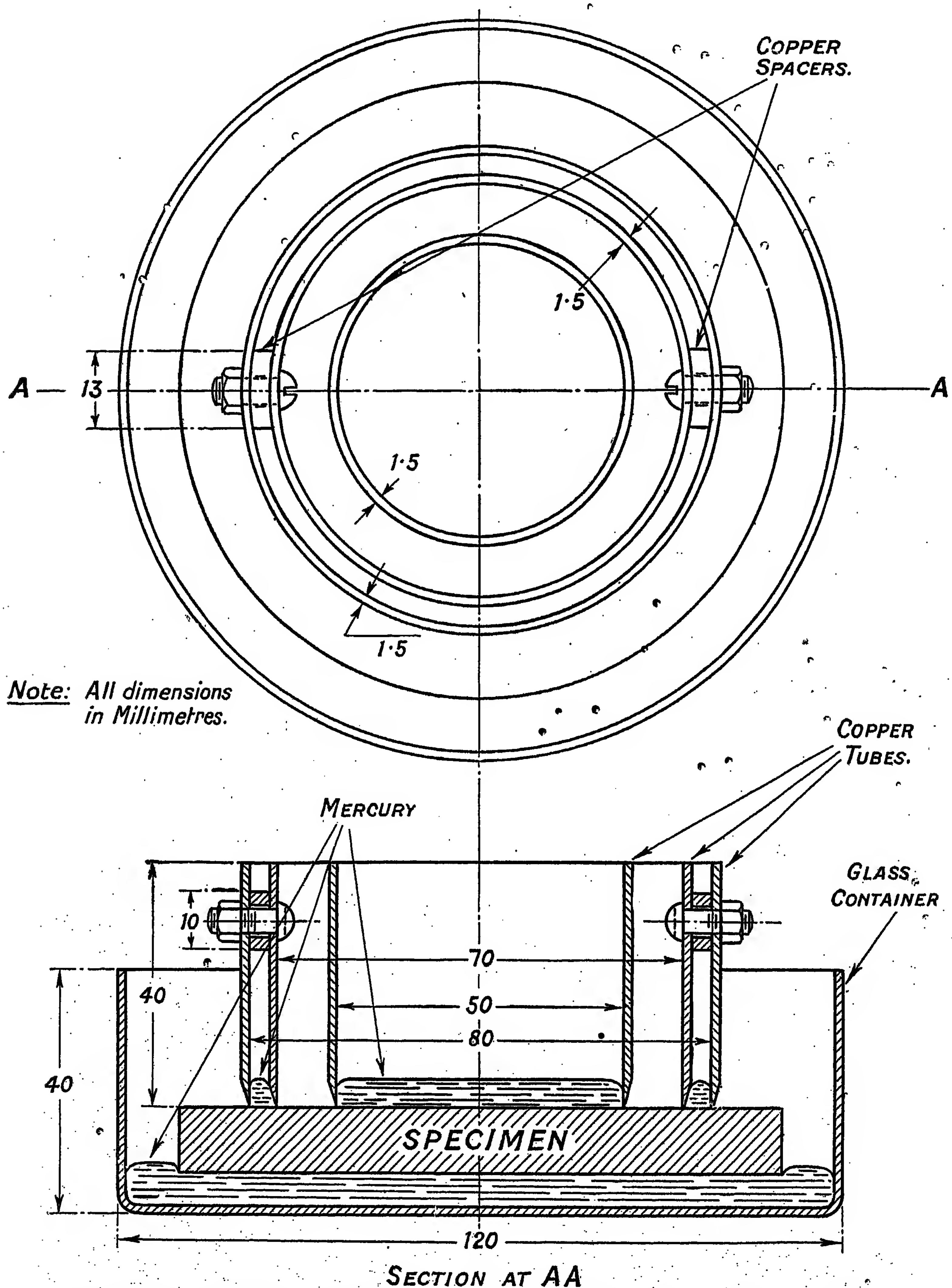


FIG. 2.—Form of Apparatus for Volume Resistivity and Surface Resistivity Tests (U.S. Bureau of Standards).

Measurements shall be made at various temperatures, including the maximum temperature at which the material is to be studied.

The specimen and the electrodes shall be exposed to the "normal" atmosphere as defined in Technical Publication Ref. A/S2, Directions for Determining the Electric Strength of Fibrous Insulating Materials, for 18 to 24 hours prior to the measurement of the resistance, and in the case of tests at room temperature whilst the test is being carried out.

A specimen 4 inches diameter shall be set up for test as shown in Fig. 1.

The resistance shall be measured at the end of each minute, over a period of ten minutes' electrification at a potential difference of 500 volts. The resistivity shall be expressed in megohms for a centimetre cube, and a curve shall be plotted showing the relationship between resistivity and time.

NOTE.—The dimensions of a suitable apparatus are shown in Fig. 2.

5. Surface Resistivity.

The specimen shall be conditioned in accordance with Clause 1 (*a*) before the surface resistivity test is carried out.

Measurements shall be made at various temperatures, including the maximum temperature at which the material is to be studied.

The specimen and electrodes shall be exposed to the "normal" atmosphere as defined in Technical Publication Ref. A/S2, Directions for Determining the Electric Strength of Fibrous Insulating Materials, for 18 to 24 hours prior to the measurement of the surface resistance, and in the case of tests at room temperature whilst the test is being carried out.

A specimen 4 inches diameter shall be set up for test as shown in Fig. 3.

The surface resistance shall be measured at the end of each minute, over a period of ten minutes' electrification at a potential difference of 500 V. The surface resistivity shall be expressed in megohms for a centimetre square, and a curve shall be plotted showing the relationship between surface resistivity and time.

NOTE.—The dimensions of a suitable apparatus are shown in Fig. 2.

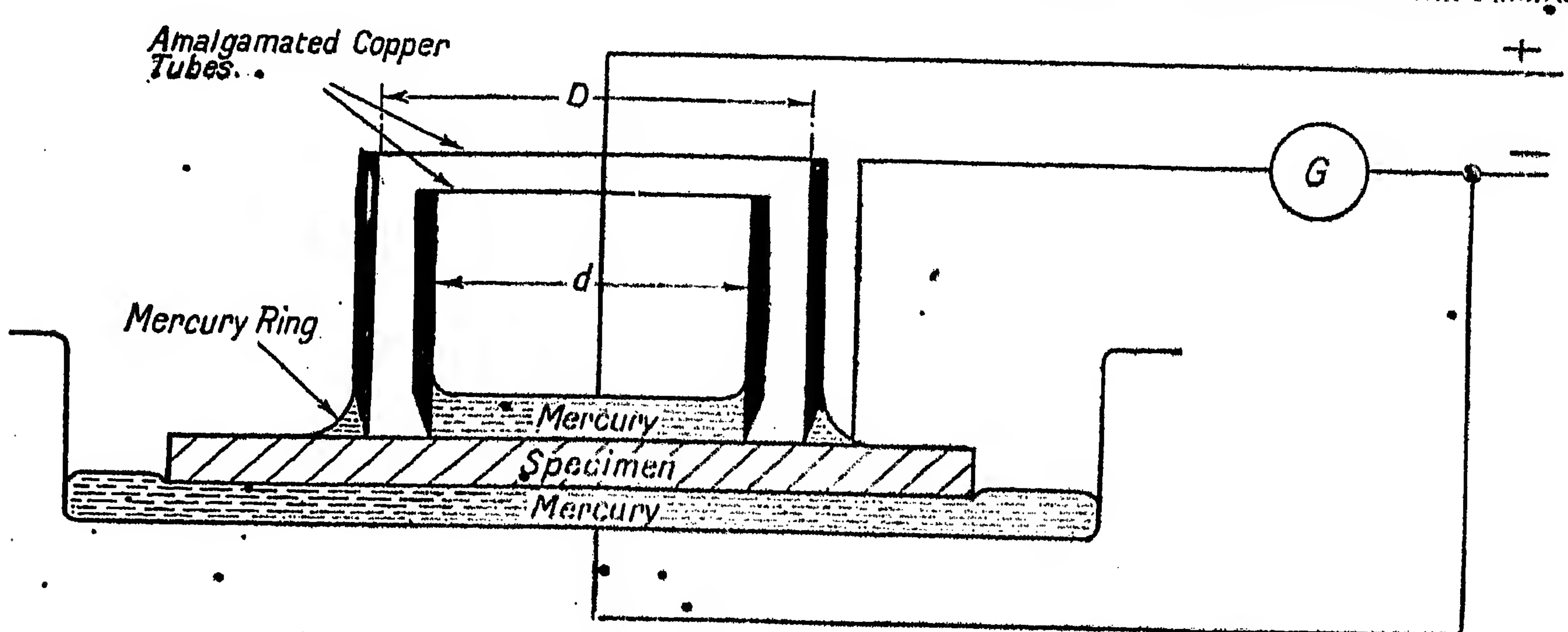


FIG. 3.—Diagrammatic Arrangement of Apparatus for Surface Resistivity Test.

6. Internal Resistance.

The specimen shall be conditioned in accordance with Clause 1 (*a*) before the internal resistance is determined.

Measurements shall be made at various temperatures, including the maximum temperature at which the material is to be studied.

The specimen and electrodes shall be exposed to the "normal" atmosphere as defined in Technical Publication Ref. A/S2, Directions for Determining the Electric Strength of Fibrous Insulating Materials, for 18 to 24 hours prior to the measurement of the internal resistance, and in the case of tests at room temperature whilst the test is being carried out.

Two holes 5 mm diameter shall be drilled to a depth equal to two-thirds of the thickness of the board. The distance between the centres of the holes shall be 15 mm. The holes shall be filled with mercury, and the resistance between them shall be measured at the end of each minute over a period of ten minutes' electrification at a potential difference of 500 volts.

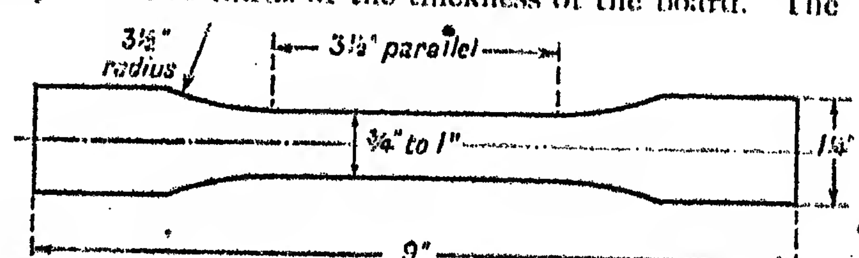


FIG. 4.—Specimen for Tensile Strength and Extension Tests on Boards.

The resistance shall be expressed in megohms, and a curve shall be plotted showing the relationship between resistance and time.

In reporting the results of the tests the thickness of the specimen shall be stated.

7. Tensile Strength and Extension.

The specimens shall be conditioned in accordance with Clause 1 (*b*) before the tests for tensile strength and extension are carried out.

The form of the specimen shall be as follows:—

(*a*) Boards, in accordance with Fig. 4.

(*b*) Tubes, in accordance with Fig. 5 (which also depicts a suitable form of grip for holding the tube in the testing machine).

The extension shall be measured on a 3-inch gauge length.

In all cases the specimens shall be tested to ascertain the ultimate tensile strength. The load shall be increased steadily at such a rate that the specimen breaks in approximately two minutes from the time of the application of the load.

The ultimate tensile strength shall be expressed in lb. per sq. in.

The test shall be carried out under the following conditions:—

(i) At a temperature from 15° C. to 25° C.

(ii) At the appropriate temperature given in Table 1, after the specimen has been immersed in the oil specified in Table 1, at the high temperature for 24 hours.

Table 1.

Temperature of Specimen in Tensile Strength and Extension Tests.

Material	Limits of Temperature, ° C.	Class of Oil
Class I, Grades A and B	90 to 95	B.S.S. No. 148 for light grade oil
Class II, Grade A..	90 to 95	
Class II, Grade B..	65 to 70	
Class I, Grade C ..	145 to 150	Mineral oil, closed flash point not less than 250° C.

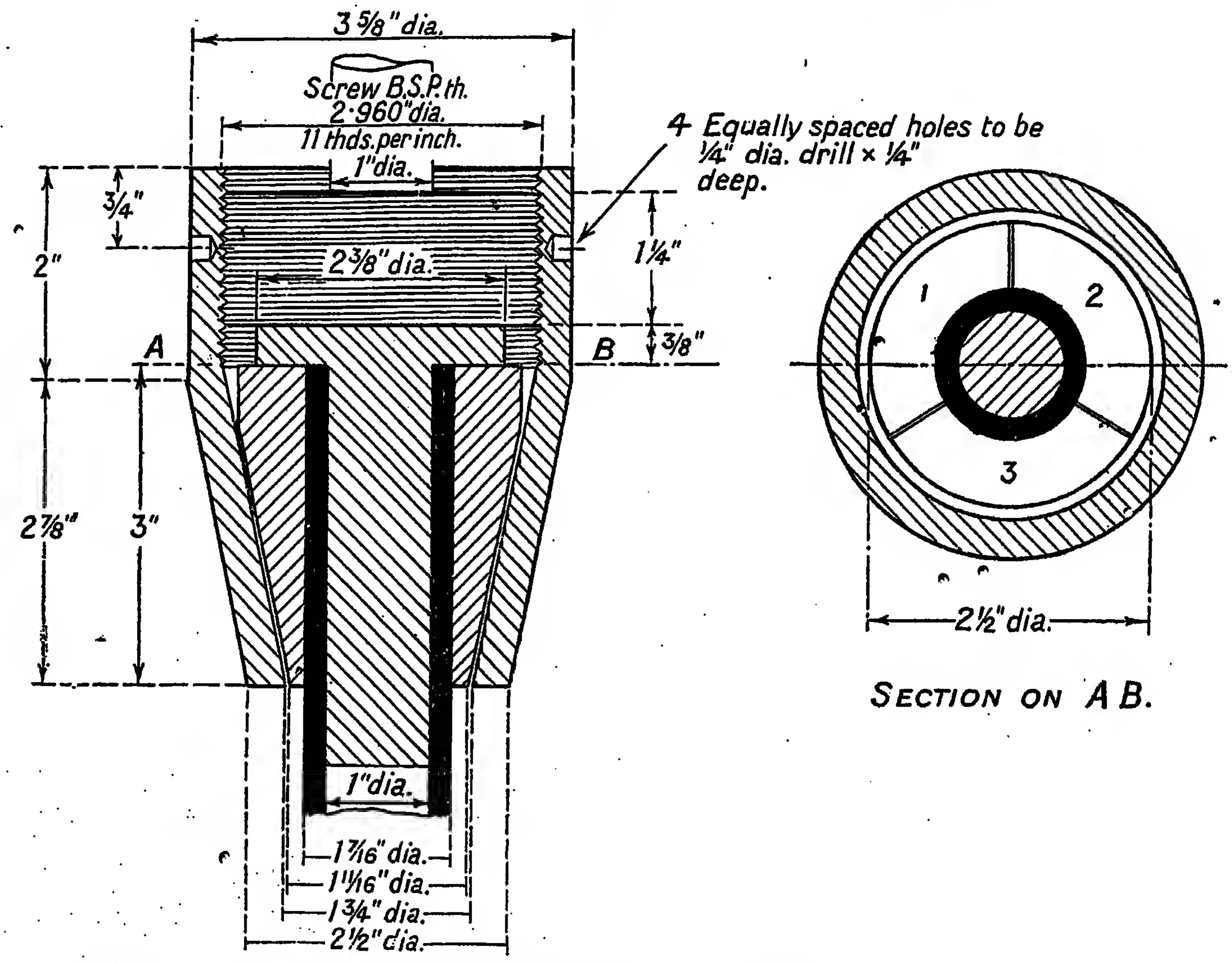


Fig. 5.—Form of Grip for holding Tube in Testing Machine for Tensile Strength and Extension Tests.

8. Compression Strength.

(Not to be applied to Class II, Grade B, material.)

(*a*) *Boards.*

The compression test shall be carried out at the appropriate temperature given in Table 2, after the specimen has been immersed in the oil specified in Table 2 at the high temperature for 24 hours.

The dimensions of the specimen shall be 1 inch cube, the specimen being built up with several layers of the material when necessary. The layers of the material shall be bedded together by the application of an initial

TABLE 2.

Temperature of Specimen in Compression Test.

Material	Limits of Temperature, °C.	Class of Oil
Class I, Grades A and B	90 to 95	B.S.S. No. 148 for light grade oil
Class II, Grade A	90 to 95	
Class I, Grade C ..	145 to 150	Mineral oil, closed flash point not less than 250° C.

load of 300 lb. per sq. in. The first measurement of the length of the specimen shall be taken under this load, which shall be included in the load registered in each case.

The load shall be applied in increments of 1 500 lb. per sq. in., each of which shall be maintained for one minute, and the yield of the specimen shall be measured at the end of each period.

The test shall be continued until the specimen has yielded 10 per cent of its original length when measured as stated above, or when the load has reached about 6 tons per sq. in.

(*b*) *Tubes.*

The form of the specimen shall be a tube, the thickness of the wall being not less than ⅛ inch, and the length equal to the external diameter of the tube. The end faces of the specimen shall be truly plane, square and parallel.

An initial load of 300 lb. per sq. in., computed on the cross-sectional area of the material, shall be applied, and the first measurement of the length of the specimen shall be taken under this load, which shall be included in the load registered in each case.

The specimen shall be heated prior to test and tested as specified in (*a*) above.

(*c*) *Cylinders.*

The form of the specimen shall be a cylinder not less than 8 inches internal diameter.

The length of the cylinder shall be equal to the internal diameter and the thickness of the wall shall be equal to 1/64th of the internal diameter.

The specimen shall be heated prior to test and tested as specified in (*b*) above.

9. SHEARING STRENGTH OF BOARDS.

The specimen shall be conditioned in accordance with Clause 1 (*b*) before the shearing test is carried out.

Materials up to and including ⅛ inch (3·2 mm) thick

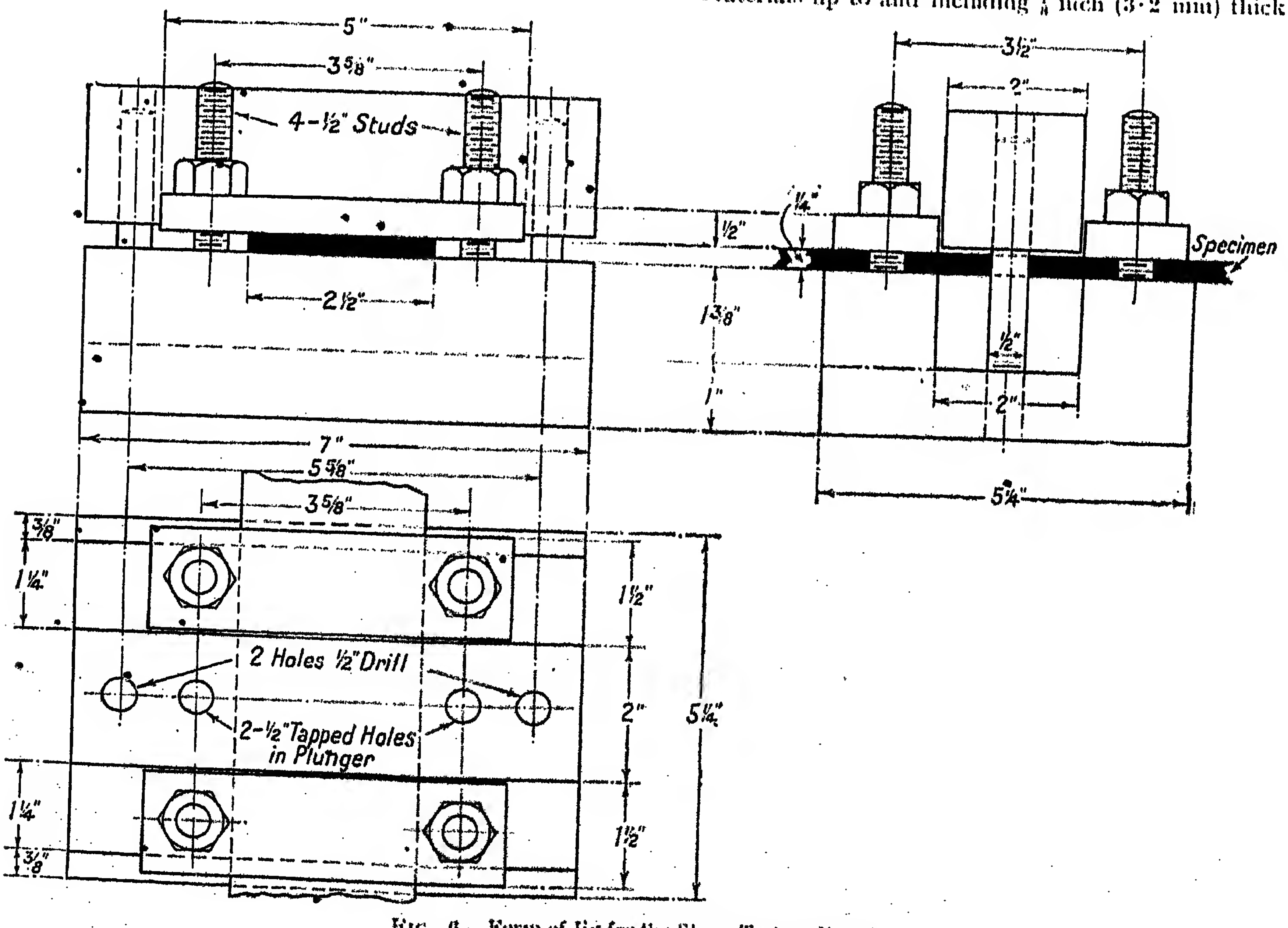


FIG. 6.—Form of Jig for the Shear Test on Boards.

shall be tested to ascertain the force required to punch a hole $\frac{1}{2}$ inch in diameter.

The load shall be applied steadily, and shall be increased at a rate of approximately 100 lb. per minute for each 1/32 inch thickness of specimen.

The clearance between the punch and the hole shall

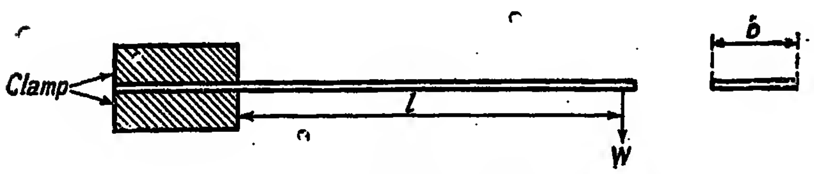


FIG. 7.—Form of Test for Stiffness or Rigidity.

be negligible, as obtained by trimming the punch with the die.

The force required to punch the hole shall be expressed in lb. per sq. in.*

Materials above $\frac{1}{8}$ inch (3·2 mm) thick shall be tested as follows:—

A load shall be applied centrally on the specimen and increased until failure occurs. The load required to cause failure and the nature of the fracture shall be stated.

(*b*) *Tubes.*

A specimen of tube shall be cut of length equal to the external diameter, and shall be subjected to a crushing load perpendicular to the axis of the tube. The load required to cause failure and the nature of the fracture shall be stated.

11. STIFFNESS OR RIGIDITY.

The specimen shall be conditioned in accordance with Clause 1 (*b*) before the stiffness test is carried out.

(*a*) *Boards.*

Materials shall be tested for stiffness or rigidity by the cantilever method as follows:—

The form and arrangement of the test shall be in accordance with Figs. 7 and 8.

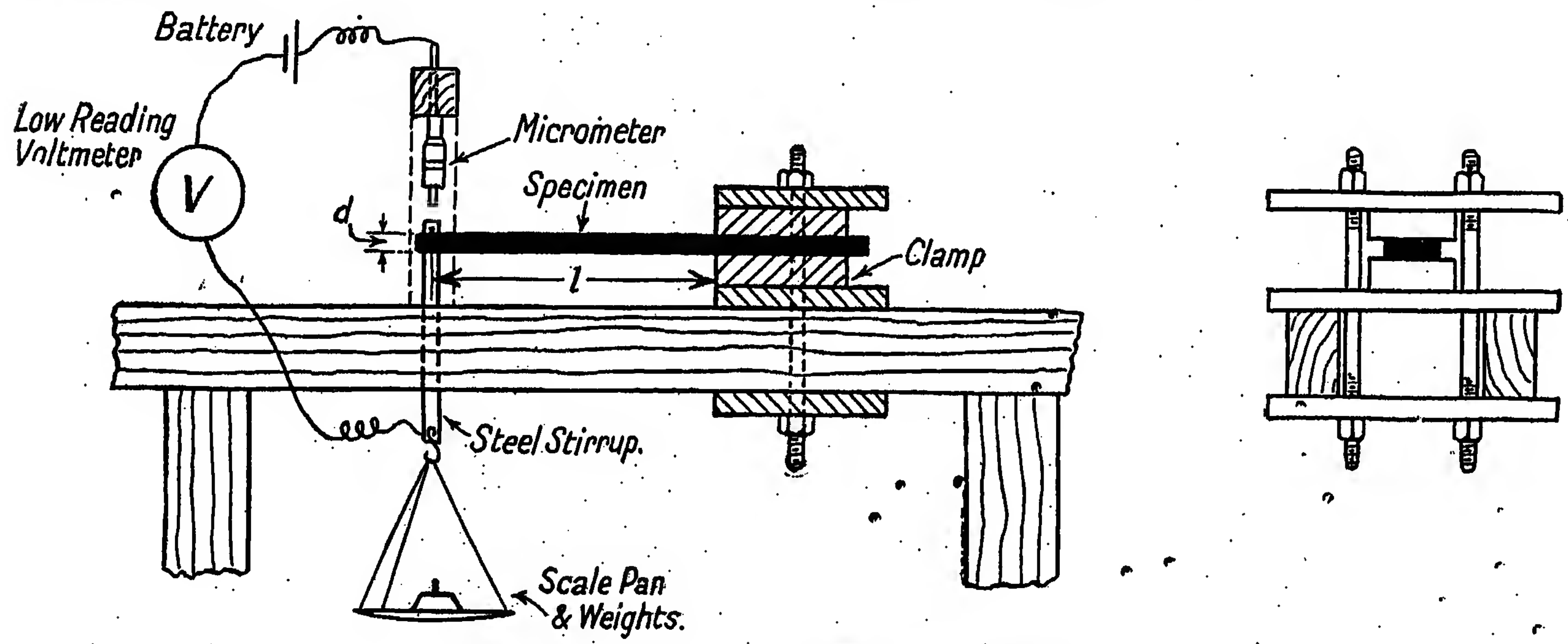


FIG. 8.—Arrangement of Cantilever Test for Boards.

A specimen, the dimensions of which shall be 5 inches (127 mm) long and $2\frac{1}{2}$ inches (64 mm) wide, shall be clamped in a shear testing jig, so that both ends of the specimen are sheared off simultaneously. The pressure required to produce shear, computed on the total area of the sections sheared, shall be expressed in lb. per sq. in.

A suitable form of jig for the shear test is shown in Fig. 6.

10. COHESION BETWEEN LAYERS (SPLITTING TEST).

The specimen shall be conditioned in accordance with Clause 1 (*b*) before the test for cohesion between layers is carried out.

(*a*) *Boards.*

A specimen 1 inch wide and of a length equal to four times the thickness of the material, plus $\frac{1}{2}$ inch, shall be supported on vee-blocks spaced apart at a distance equal to four times the thickness of the material under test.

The specimen shall be firmly fixed in clamps and the stirrup and scale pan placed in position as shown in Fig. 8. A measurement shall be made of the unsupported end below datum as follows:—

An inside micrometer shall be clamped above the stirrup. The electric circuit shall be as shown in Fig. 8. The micrometer screw shall be turned until the circuit is closed (as indicated by the voltmeter), and the micrometer reading shall then be taken.

Small equal increments of load shall be applied and the corresponding increments in deflection measured immediately. Each increment of load shall be applied as soon as the deflection for the previous load increment has been read. Readings shall only be taken for the range during which the increment of load is proportional to the increment of deflection.

The dimensions of the specimen shall be as follows:—

For specimens not exceeding 1/6 inch thick:

Cantilever length = 2 inches
Breadth = $\frac{3}{4}$ inch

The increments of deflection shall not exceed 0·010 inch.

* In a future edition of this Specification it is probable that the shear stress will be substituted for the pressure required to punch the hole.

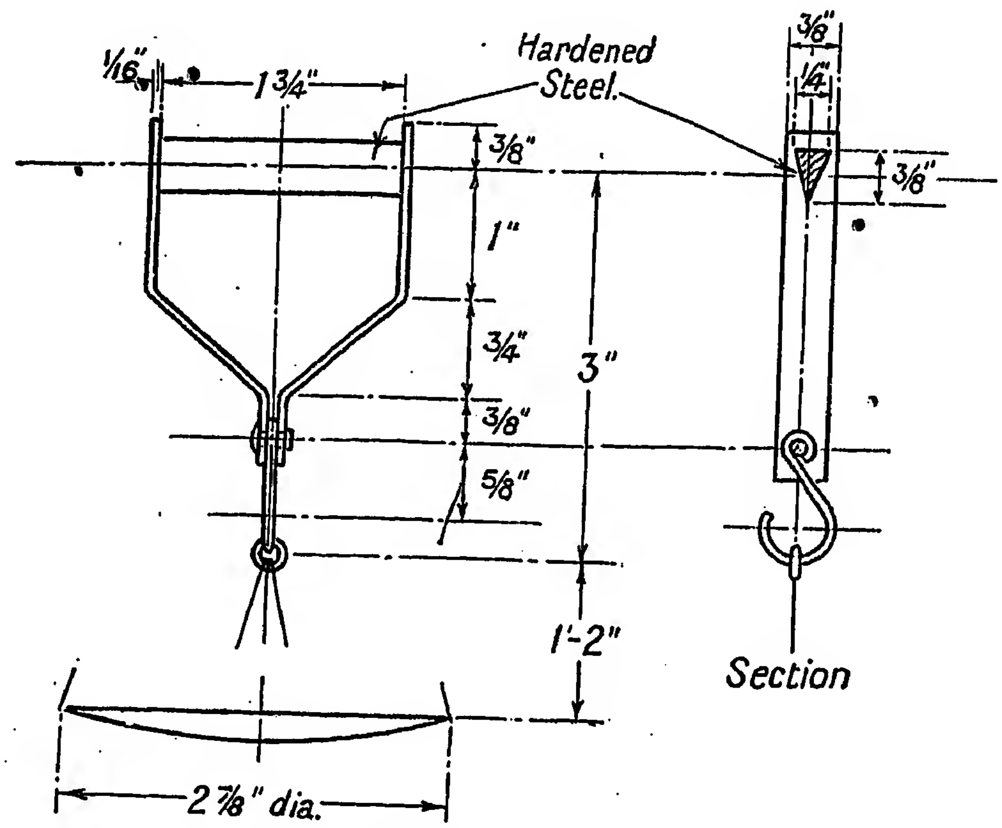


FIG. 9.—Form of Knife-edge Balance for Cantilever Test.

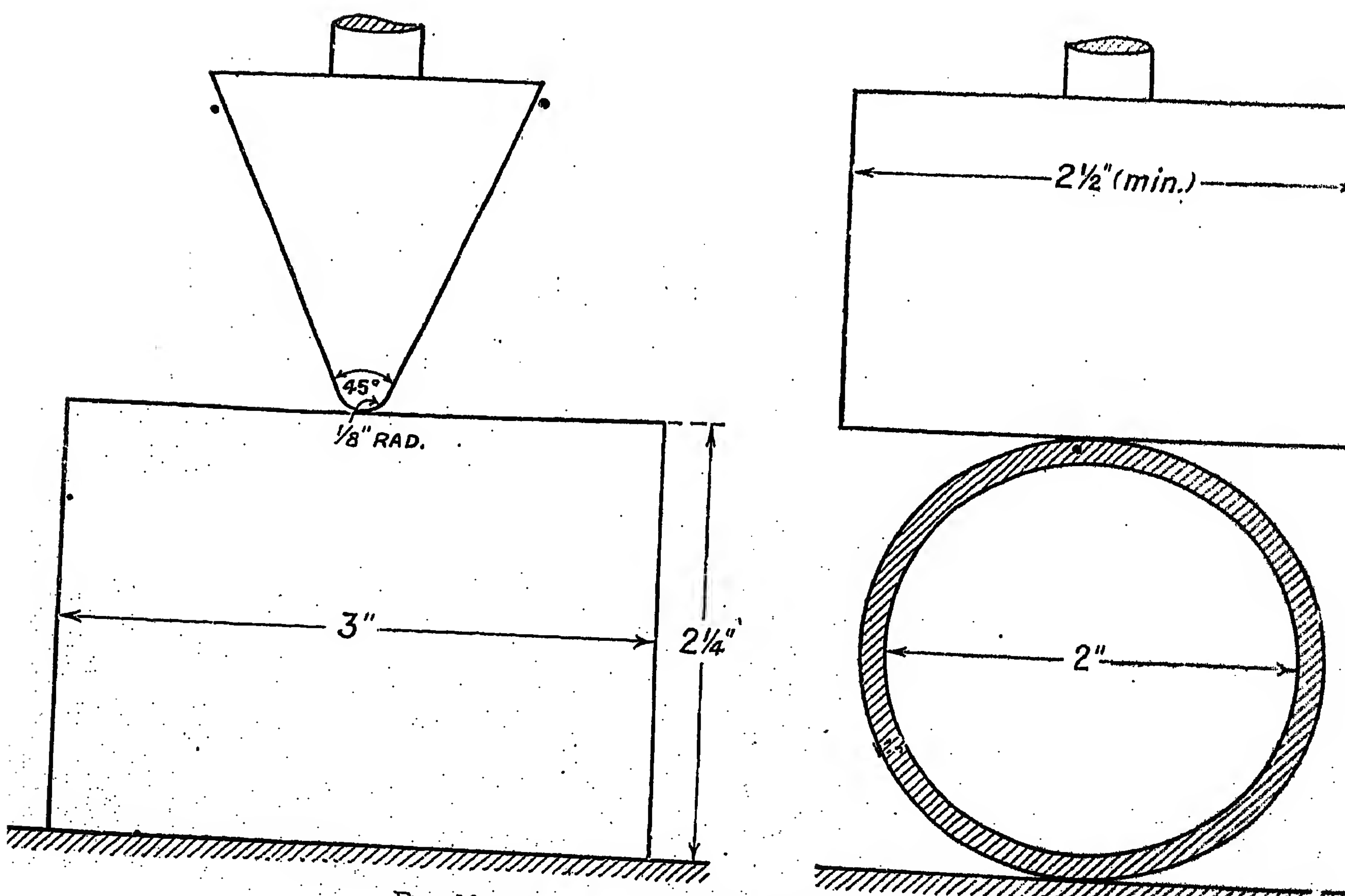


FIG. 10.—Arrangement of Stiffness Test for Tubes.

For specimens exceeding 1/16 inch thick the cantilever length shall be from 3 inches to 9 inches according to the stiffness of the material.

The breadth of the specimen shall be one-fifth of the cantilever length.

The increment of deflection shall not exceed 0·015 inch.

Young's Modulus E shall be computed from the following formula :—

$$E = \frac{4Wl^3}{bd^3y}$$

where W = average increment of load, lb.,
l = cantilever length, inches,
b = breadth of specimen, inches,
d = thickness of specimen, inches,
y = average increment of deflection, inches.

When the final increment of deflection has been measured as described above, the load shall not be removed. The increment of deflection shall be re-measured after 1 minute, 10 minutes, 1 hour and 18 hours respectively.

After the 18-hour test has been completed, tests at loads of 0·66 and 1·5 times, respectively, the value of the load employed in the 18-hour test shall be applied to the specimen, and the increments of deflection shall be re-measured as before in the prolonged test.

NOTE.—A suitable form of knife-edge balance for use in the cantilever test is shown in Fig. 9.

(*b*) *Tubes.*

A tube 3 inches long, 2 inches internal diameter and 2¼ inches external diameter shall be set up in a compression testing machine as shown in Fig. 10.

The load shall be applied to the top of the specimen and midway between the ends, by means of a wedge-shaped plunger not less than 2½ inches wide, the bottom edge of which is rounded to a radius of ⅛ inch. The angle of the wedge shall be approximately 45 degrees, and its axis shall be at right angles to the axis of the tube as shown in Fig. 10. The load shall be increased by steps, and sufficient readings of the load and travel of the plunger taken up to the load at which failure occurs to enable a stress-strain curve to be plotted.

12. SHRINKING, WARPING AND SWELLING.

The following tests shall be conducted after the specimens have been exposed for 18 to 24 hours to the "normal" condition as defined in Technical Publication Ref. A/S2, Directions for Determining the Electric Strength of Fibrous Insulating Materials.

(*a*) *Shrinkage.*

(i) *Test in Air.*

In the case of boards, the test for shrinkage shall be carried out on a specimen about 4 inches square.

The length and width respectively of the specimen shall be measured at ten points equally spaced along each of two edges at right angles. The thickness of the specimen shall be the mean of ten measurements of thickness taken at points equally spaced around the edges. The measurements shall be made by means of a micrometer or other suitable method.

In the case of tubes, the test for shrinkage shall be carried out on a specimen the length of which shall be not less than three times the external diameter.

The internal and external diameters of the specimen shall be measured in two directions at right angles. The measurements shall be made by means of a micrometer or other suitable method.

The specimen shall be dried for 48 hours by heating uniformly in an oven at the appropriate temperature given in Table 3, and the dimensions shall then be measured at the same points as before at atmospheric temperature.

TABLE 3.

Temperature of Specimen in Shrinkage Test in Air.

Material	Limits of Temperature, ° C.
Class I, Grades A and B	105 to 110
Class I, Grade C	160 to 165
Class II, Grade A	105 to 110
Class II, Grade B	80 to 85

Comparison shall be made between the mean values of the dimensions before and after the heat treatment, and the percentage difference, computed on the original mean values respectively, shall be stated, the original mean values being given.

(ii) *Test in Oil* (*not to be applied to Class II, Grade B Material*).

In the case of boards, the diameters of a ring approximately 4 inches internal diameter and 6 inches external diameter shall be measured longitudinally and transversely. The ring shall be immersed in the oil specified in Table 4 for 120 hours at the appropriate temperature given in Table 4. The diameters shall then be measured again as before at atmospheric temperature. Comparison shall be made between the values of the diameters before and after the immersion in oil, and

TABLE 4.

Temperature of Specimen in Shrinkage Test in Oil.

Material	Limits of Temperature, ° C.	Class of Oil
Class I, Grades A and B	115 to 120	B.S.S. No. 148 for light grade oil
Class II, Grade A	115 to 120	
Class I, Grade C ..	170 to 175	Mineral oil, closed flash-point not less than 250° C.

the percentage differences computed on the original values shall be stated.

In the case of tubes, the internal and external diameters of a specimen, the length of which shall be not less than three times the external diameter, shall be measured in two directions at right angles. The tube shall be heated in oil as specified above, and the diameters shall then be measured again at the same points as before at atmospheric temperature.

Comparison shall be made between the mean values of the internal and external diameters respectively before and after the immersion in oil, and the percentage differences computed on the original mean values shall be stated, the original mean values being given.

(b) Warping.

Warping shall be determined by the following method :—

(i) *Boards.*

A specimen 6 inches square shall be dried for 48 hours at the appropriate temperature given in Table 3. It shall then be placed on a flat surface not less than 7 inches square, and a flat metal plate 6 inches square shall be placed on the specimen, so that the edges of the plate and the specimen coincide. The weight of the upper plate shall not exceed 8 ounces. The distances between the four corners of the under surface of the upper plate and the corresponding points on the upper surface of the lower plate shall be measured. The sum of the four readings shall be compared with four times the original mean thickness of the specimen before drying, and the percentage increase computed on four times the original thickness shall be stated.

(ii) *Tubes.*

A straight tube, the length of which shall be 24 times the internal diameter, shall be dried for 48 hours at the appropriate temperature given in Table 3. The tube shall then be tested by means of a straight-edge or other suitable method, and the maximum deviation from straightness shall be stated, the internal and external diameters of the tube being given.

13. Machining Properties.

The specimen shall be conditioned in accordance with Clause 1 (*b*) before the machining tests are carried out.

The machining properties of the material shall be determined by turning, milling, drilling, countersinking and punching specimens. The effect on the material with respect to cracking, splitting or chipping shall be stated.

Boards shall be tested by being tapped with a No. 0 B.A. tap. Tubes shall be tested by being screwed, externally and internally, with 11 B.S.W. threads per inch, cut with a tool by an operator experienced in working with this class of material. The effect on the material with respect to cracking, splitting or chipping shall be stated.

Note.—The manufacturer of the material should be asked to state the cutting speed, depth of cut, rate of feed and lubricant, if any, to be employed in carrying out the machining tests.

14. Freedom from Chemical Reaction.

The chemical tests shall be carried out on the material as received without conditioning.

The material shall be tested * for the presence of the following :—

Ammonia. (Does not apply to Class II material.)
Phenol. (Does not apply to Class II material.)
Free Mineral Acids.
Organic Acids. (Does not apply to Class I material.)
Alkalis.
Lime.
Chlorides.

The tests shall be carried out as follows :—

(a) Free Ammonia.

Two grammes of the material are pulped with 200 cm^3 of distilled water free from ammonia and boiled for a short time under reflux condensation. The filtrate is distilled until 100 cm^3 have come over, and the distillate is made up to 250 cm^3. Varying aliquot amounts from 5 cm^3 to 100 cm^3 are tested with Nessler's reagent until a suitable coloration is found. This is then matched by means of standard ammonium chloride solution by the usual colorimetric method as employed in water analysis.

(b) Combined Ammonia.

The distillation residue from the above determination is made up to 200 cm^3 with water free from ammonia. A little caustic soda is added, and the processes of distillation and Nesslerization are repeated as above.

(c) Phenol.

Ten grammes of material are pulped with 200 cm^3 of water, and the whole mixture distilled until about 100 cm^3 have come over.

To the distillate so much dilute iodine solution is added as is needed just to give a faint coloration with starch-paste. Phenol is then determined by the Koppeschaar method, i.e. sodium bromate solution and acid are added, and after tribromophenol has separated out, the unused bromine is titrated back with KI and thiosulphate.

(d) Acids or Alkalies.

Ten grammes of the material are pulped with 200 cm^3 of distilled water and gently boiled for one † hour. The cooled liquid is filtered perfectly clear by the aid of a pump. The filtrate is tested with phenolphthalein.‡

* It is important to reduce the material to as finally divided a condition as possible, since fully-stoved synthetic resins cannot be brought into solution except by the most destructive solvents. In some cases soaking in water and subsequent pounding in a mortar will reduce the material to a pulp in which the synthetic resin is in a sufficiently fine state of division. In more refractory cases it will be necessary to pulverize the material in a laboratory mill. A suitable method is wet grinding in a cone mill, after the material has been cut into the smallest possible pieces.

† It has been found that alkali is sometimes difficult to remove from pulp. It is recommended that if on testing after one hour's boiling alkalinity is indicated, the pulp should be re-boiled with another 200 cm^3 of distilled water, and further boilings given if considered necessary.

‡ If the solution to be titrated is not coloured, methyl orange has been found reliable.

If acid, it is titrated with $\frac{N^*}{100}$ caustic soda; if alkaline, with $\frac{N^*}{100}$ hydrochloric acid. Should the filtrate be very dark, alkali blue 6B may be used as indicator. If alkali blue 6B is not available, and phenolphthalein is used, the solution must be suitably diluted with a neutralized diluent, or alcoholic or ethereal extracts must be employed. When a large amount of free acid or alkali † is found, it is advisable to boil the residue with fresh water, titrate again, and repeat as requisite.

The acidity or alkalinity shall be expressed as—

"Equivalent to — per cent of SO_3," or
"Equivalent to — per cent of NaOH."

(e) *Organic Acids.*

Ten grammes of the conditioned sample shall be extracted to exhaustion with 100 cm^3 of methylated spirit in a soxhlet apparatus. The alcoholic extract thus obtained shall be cooled, and to it shall be added 50 cm^3 of benzene and a considerable excess of N/2 sodium hydroxide (e.g. 50 cm^3); the mixture shall be well shaken for about five minutes, and then the excess of alkali back titrated with N/2 H_2SO_4 and phenolphthalein.

(f) *Lime and Chlorides.*

The lime and chlorides shall be determined by the usual laboratory methods from the ash after the incineration of the material.

15. Effects of Acid and Alkali.

The tests for the effect of acid and alkali shall be carried out on the material as received without conditioning.

Specimens, the dimensions of which shall be similar to those specified in Clause 10, shall be immersed in the following reagents:—

(a) A sulphuric acid solution, specific gravity 1·25, for 24 hours at a temperature of 40° C.
(b) A 5 per cent solution of caustic soda, for 24 hours at a temperature of 100° C. (Not to be applied to Class II material.)
(c) A 10 per cent solution of common salt, for 24 hours at a temperature of 100° C.

After removal from the reagents, the specimens shall be tested for cohesion between layers in accordance with Clause 10, and their condition with respect to disintegration, blistering, warping, splitting or other deterioration shall be stated.

16. Effect of Oil.

(Not to be applied to Class II, Grade B, material.)

The specimen shall be conditioned in accordance with Clause 1 (b) before the effect of oil is determined.

A specimen shall be immersed in the oil specified in Table 4 for seven days continuously at the appropriate temperature given in Table 4. At the end of this period the condition of the specimen with respect to disintegration, warping, splitting, blistering, softening or other deterioration shall be stated.

17. Effect of Prolonged Heating at High Temperature.

(Not to be applied to Class II material.)

The specimen shall be conditioned in accordance with Clause 1 (b) before the effect of prolonged heating at high temperature is determined.

A specimen shall be heated at the appropriate temperature given in Table 5 for seven days continuously

TABLE 5.

Temperature of Specimens in Prolonged Heating at High Temperature Test.

Material	Limits of Temperature, °C.
Class I, Grades A and B	150 to 155
Class I, Grade C	200 to 205

in air, and another specimen shall be heated at the same temperature for seven days continuously in mineral oil having a closed flash-point not less than 250° C. After the heat treatment, the condition of the specimens with respect to disintegration, warping, splitting, blistering, softening or other deterioration shall be stated.

18. Water Absorption.

The specimen shall be conditioned in accordance with Clause 1 (b) before the test for water absorption is carried out.

A sample of board $1\frac{1}{2}$ inches square, or a tube $1\frac{1}{2}$ inches long, shall be weighed. The board specimen shall have the four edges, and the tube specimen the two ends, freshly cut before being used for the test. The specimen shall then be immersed in water at a temperature from 15° C. to 25° C. After 24 hours' immersion it shall be taken from the water, and, after removing the surface moisture by wiping, weighed again.

The specimen shall then be replaced in the water, and after six days' immersion re-weighed with the same precautions as before. The weight shall be taken to the nearest milligramme in each case.

The percentage absorption of water in each case shall be computed on the original weight of the specimen, and the orginal dimensions of the specimen shall be stated.

When it is desired to distinguish between the absorption in the longitudinal, transverse and perpendicular directions respectively, the appropriate surfaces of the specimen shall be coated with a waterproof varnish before the test for water absorption is carried out.

* When a large amount of acid or alkali is present $\frac{N}{10}$ solution may be used.

† It has been found that alkali is sometimes difficult to remove from pulp. It is recommended that if on testing after one hour's boiling alkalinity is indicated, the pulp should be re-boiled with another 200 cm^3 of distilled water, and further boilings given if considered necessary.

SCHEDULE.

Service Conditions*				Conditioning of Specimen for Test	Test recommended to determine the Suitability of the Material
Electric Stress	Frequency	Mechanical Stress	Temperature		
(1) Low	Power	Low	Low	Normal (Clause 1 (a))	Electric strength
Low	Power	Low	Low	Dry (Clause 1 (b))	Machining properties
(2) Low	Power	Low	High	Normal (Clause 1 (a))	Electric strength
Low	Power	Low	High	Dry (Clause 1 (b))	Machining properties
Low	Power	Low	High	Dry (Clause 1 (b))	Effect of prolonged heating at high temperature, followed by test for cohesion between layers
(3) Low	Power	High	High	Normal (Clause 1 (a))	Electric strength
Low	Power	High	High	Dry (Clause 1 (b))	Machining properties
Low	Power	High	High	Dry (Clause 1 (b))	Effect of prolonged heating at high temperature, followed by test for cohesion between layers, in which transverse modulus of elasticity should be determined.
(4) High	Power	High	High	Normal (Clause 1 (a))	Electric strength, with special reference to its value at high temperature
High	Power	High	High	Dry (Clause 1 (b))	Machining properties
High	Power	High	High	Dry (Clause 1 (b))	Effect of prolonged heating at high temperature, followed by test for cohesion between layers, in which the transverse modulus of elasticity should be determined
(5) Low	Radio	Low	Low	Normal (Clause 1 (a))	Power factor and permittivity at radio frequencies
Low	Radio	Low	Low	Dry (Clause 1 (b))	Machining properties
(6) High	Radio	High	High	Normal (Clause 1 (a))	Power factor and permittivity at radio frequencies
High	Radio	High	High	Dry (Clause 1 (b))	Machining properties
High	Radio	High	High	Dry (Clause 1 (b))	Effect of prolonged heating at high temperature, followed by test for cohesion between layers, in which the transverse modulus of elasticity should be determined
For use in a very damp atmosphere ..				Damp (Clause 1 (a))	Electric strength
				Tropical (Clause 1 (a))	Electric strength
				Dry (Clause 1 (b))	Water absorption
When subjected to considerable tensile stress				Normal (Clause 1 (a))	Electric strength
				Dry (Clause 1 (b))	Tensile strength and extension
				Dry (Clause 1 (b))	Machining properties
When subjected to considerable compression stress				Normal (Clause 1 (a))	Electric strength
				Dry (Clause 1 (b))	Compression strength
				Dry (Clause 1 (b))	Machining properties
When subjected to considerable shearing stress				Normal (Clause 1 (a))	Electric strength
				Dry (Clause 1 (b))	Shearing strength
				Dry (Clause 1 (b))	Machining properties
When high resistivity is required				Normal (Clause 1 (a))	Resistivity
				Normal (Clause 1 (a))	Internal resistance
				Normal (Clause 1 (a))	Electric strength
				Dry (Clause 1 (b))	Machining properties
When high surface resistivity is required ..				Normal (Clause 1 (a))	Surface resistivity
				Normal (Clause 1 (a))	Internal resistance
				Normal (Clause 1 (a))	Electric strength
				Dry (Clause 1 (b))	Machining properties

* Typical examples of the use of material under these conditions are as follows:—

(1) Terminal boards for use under oil.
(2) Insulating parts of resistances for use on low pressure circuits.
(3) Spacing pieces, etc., on rotating fields of alternators.
(4) Spacing pieces, etc., of large oil-immersed transformers.
(5) Insulating parts of wireless receiving apparatus.
(6) Insulating parts of wireless transmitting apparatus.

19. Determination of Density.

The specimen shall be conditioned in accordance with Clause 1 (*b*) before the density is determined.

The density, expressed in grammes per cm^3, shall be ascertained by weighing and measuring a sample of board $1\frac{1}{2}$ inches square or a tube $1\frac{1}{2}$ inches long.

20. Power Factor and Permittivity at Radio Frequencies.

Methods of test suitable for synthetic resin varnish-paper (fabric) boards are being developed by the Association.

21. Softening Point.

The specimen shall be conditioned in accordance with Clause 1 (*b*) before the softening point is determined.

(*a*) *Boards.*

The softening point of the material shall be determined on a specimen of dimensions similar to those of the specimen employed in the Stiffness Test, Clause 11 (*a*). The specimen shall be set up for test in a manner similar to that described in Clause 11 (*a*).

A load equal to half the value of the load employed in the 18-hour test in Clause 11 (*a*) shall then be applied. The apparatus shall be arranged in a suitable heated chamber, the temperature of which shall be gradually increased at the rate of 10° C. per hour until the specimen fails completely. The initial temperature shall be as follows:—

(i) For Class I materials, 100° C.
(ii) For Class II materials, 60° C.

The deflection at each 5° C. increment of temperature shall be noted, and complete failure shall be deemed to have occurred when the rate of deflection of the specimen is seen to increase rapidly without appreciable increase of temperature.

(*b*) *Tubes.*

The softening point of the material shall be determined on a specimen of dimensions similar to those of the specimen employed in the Stiffness Test, Clause 11 (*b*). The specimen shall be set up for test in a manner similar to that described in Clause 11 (*b*).

A load equal to half the value of the load at which failure occurs in Clause 11 (*b*) shall be applied. The test shall then be carried out in the same manner as described in (*a*) above.

22. Effect of Vibration and Impact.

Note.—Methods of test are under consideration.

23. Effect of Electric Arc.

The specimen shall be conditioned in accordance with Clause 1 (*b*) before the test for the effect of electric arc is carried out.

The specimen shall consist of two strips of the material 6 inches long and 2 inches wide, which shall be clamped together with a piece of 0·036 inch diameter copper wire between them, laid centrally along their length.

The copper wire shall be fused by being connected across a 500-volt D.C. circuit in which there is a total non-inductive resistance of such a value as to limit the current to 100 amperes. The fuse may be short circuited by a switch whilst the current is being adjusted.

The test shall be repeated at intervals of two minutes until the carbonized surface of the material acts as a conductor and the arc does not extinguish itself. The number of times the copper wire can be fused before this state is reached and the condition of the surface of the material shall be stated.

Note.—This material is not of an arc-resisting character, and should not be used in service in such a manner that it will under normal conditions be exposed to an arc or flame.

Schedule.

When it is desired to study the materials covered by this Specification for specific purposes, and it is obviously unnecessary to apply the whole of the tests described in Section II, the abridged series of tests outlined in the Schedule on page 171 should be applied.

DIRECTIONS FOR THE STUDY OF VARNISHED COTTON CLOTH (EXCLUDING ADHESIVE TAPE).

[REPORT (REF. A/S7) RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

CONTENTS.

PREFACE.

It has been found from experience that considerable differences exist in the electrical and mechanical properties of varnished cotton cloth supplied to electrical manufacturers from different sources. Hitherto it has been too commonly the practice to compare various samples of varnished cloth by a crude test for electric strength and perhaps a tensile strength test. It is clear that such tests by no means determine the relative merits of different samples with respect to their suitability for use in electrical machinery. This Specification has, therefore, been drafted, in which directions are given for a comprehensive study of the electrical and mechanical properties of varnished cloths with a view to the adoption by makers and users of uniform methods of test, and ensuring that the important properties of the material with respect to service conditions may be thoroughly investigated.

The ability of varnished cloth to withstand a relatively high alternating electric stress for a prolonged period without breakdown is of vital importance, but electric strength tests, as frequently carried out, are of little value towards securing this result. Appropriate tests will be found referred to in Clauses 10 and 11.

This Specification is not intended for use as a purchasing specification, but it is issued in the belief that it will lead to such improvements that all varnished cloth supplied to the electrical industry will be at least equal to the best now obtainable, and that there will be in time considerable further improvement.

With further experience in the use of the methods of test suggested herein, and after they have come into general use, the Association will be in a position to make recommendations to the British Engineering Standards Association for the issue of a Purchasing Specification for Varnished Cotton Cloth.

The Director of the E.R.A. will value comments and criticism from those who have occasion to use any of the tests given in this Specification.

I. DEFINITIONS.

(a) *Yarn.*

The term "yarn" denotes the spun cotton (see Clause 2).

(b) *Fabric.*

The term "fabric" denotes the woven yarn (see Clause 3).

(c) *Varnish.*

The term "varnish" denotes any substance, used alone or dissolved in a suitable solvent, that yields an insulating film when applied to the fabric.

(d) *Unvarnished.*

The term "unvarnished" denotes that the fabric has not been varnished or impregnated with insulating compounds, but embraces material which has been subjected to preparatory treatments such as those referred to in Clause 4.

(e) *Varnished.*

The term "varnished" denotes fabric that has been varnished or impregnated with insulating compounds.

(f) *Varnished Cloth.*

The term "varnished cloth" denotes the finished material suitable for use as a dielectric.

II. PREPARATION OF THE FABRIC BEFORE VARNISHING.

1. General.

The relative merits of various classes of cotton, various methods of spinning and weaving, and various treatments in manufacture before varnishing should be studied with respect to the electrical and mechanical properties and uniformity of the finished cloth.

2. Classification of Cotton.

The following classes of cotton should be investigated :

(*a*) Sea Island.
(*b*) Egyptian.
(*c*) American.
(*d*) Indian.

3. Spinning and Weaving.

The effect of the following should be ascertained :—

(*a*) Count of yarn.
(*b*) Twist of yarn.
(*c*) Type of weave.
(*d*) Closeness of weave.

4. Processes of Treatment during the Preparation of the Fabric.

The effect of the following processes should be ascertained :—

(*a*) Sizing.
(*b*) Bleaching.
(*c*) Parchmentising.
(*d*) Mercerising.
(*e*) Singeing.
(*f*) Dressing (nature and amount).
(*g*) Calendering.

5. Physical Tests on the Fabric before Varnishing.

Note.—The tests to be carried out on the fabric before varnishing will be given in another document.

III. VARNISH TREATMENT.

6. Classes of Varnish.

The relative merits of the following classes of varnish require investigation :—

(*a*) Oil, linseed or other drying oils.
(*b*) Oil and resin or gum resins.
(*c*) Shellac or other natural gums.
(*d*) Bituminous or asphaltic, including natural and artificial asphalt and pitches.
(*e*) Synthetic resins, of which phenol and formaldehyde condensation products are typical.

7. Method of Varnishing.

Note.—Instructions on the method to be employed in varnishing the fabric are under consideration.

IV. METHODS OF TEST.

When reporting the results of any test the thickness of the material, with the varnish removed, and the count of yarn, and number of threads per inch of warp and weft shall be stated.

8. Maturing of Varnished Cloth.

The varnished cloth shall be stored in a dry cool room, not artificially conditioned, for at least three months before the tests specified below are carried out.

9. Conditioning of Specimens for Test.

The varnished cloth shall be conditioned as described below.

(*a*) *"Normal" Condition.*

This is obtained by permitting the material to absorb its normal quantity of moisture by exposing it to an atmosphere of 75 per cent relative humidity at a temperature from 15° C. to 25° C. for 18 to 24 hours.

Note.—The specified relative humidity may be obtained by the use of a solution of sulphuric acid in water, specific gravity 1·223.

(*b*) *"Dry" Condition.*

This is obtained by removing from the material as much as possible of its free natural moisture, by heating it at a temperature from 75° C. to 80° C. for two to three hours.

(*c*) *"Damp" Condition.*

This is obtained by exposing the material to an atmosphere of not less than 95 per cent relative humidity at a temperature from 15° C. to 25° C. for 18 to 24 hours.

(*d*) *"Tropical" Condition (for use when required).*

This is obtained by exposing the material to an atmosphere of not less than 90 per cent relative humidity at a temperature from 45° C. to 50° C. for 18 to 24 hours.

(*e*) *"Recovered" Condition.*

This is obtained by heating the material at a temperature from 75° C. to 80° C. for 18 to 24 hours and subsequently exposing it to Normal Condition as in Clause 9 (*a*) for one week.

Note (i).—If in (*c*) or (*d*) the material is removed from the atmosphere of specified humidity before testing, precaution must be taken to prevent appreciable change in the condition of the material from this cause.

Note (ii).—When testing the electric strength of the material at the high temperatures the electrodes should be raised to the high temperature before the material is removed from the atmosphere of specified humidity.

10. Highest maintained Alternating Electric Stress.

The test shall be carried out in accordance with Technical Publication Ref. A/S2, Directions for Determining the Electric Strength of Fibrous Insulating Materials, Appendix II.

The test shall be carried out after the material has been conditioned as specified in Clause 9 (*a*), (*b*) and (*e*) of this Specification.

Under special circumstances the test shall also be carried out after the material has been conditioned as specified in Clause 9 (*c*) and (*d*) of this Specification.

11. Electric Strength.

The tests shall be carried out in accordance with Technical Publication Ref. A/S2, Directions for Determining the Electric Strength of Fibrous Insulating Materials, Part II, Abridged Tests.

The varnished cloth shall be tested under the states given in (*a*) and (*b*) below, at the temperatures specified in Ref. A/S2, Part II, Abridged Tests.

(*a*) *Test in Free State.*

The varnished cloth shall be tested in a free state, i.e. unstressed.

(*b*) *Test under Tension.*

The varnished cloth shall be tested in strips of convenient width whilst subjected to various values of tensile stress ranging from 0·5 to 1·5 lb. per mil thickness per inch width of strip. The load shall be maintained for 5 minutes before the electric stress is applied. The appearance of the varnish film when the electric stress is applied shall be stated.

Tests shall be carried out with the load applied in the direction of the warp, the weft and the bias at an angle of 45° respectively.

12. Tensile Strength.

The varnished cloth shall be brought to the normal condition as specified in Clause 9 (*a*), before the test for tensile strength is carried out.

Nine specimens shall be cut in such a manner as to be representative of the bulk of the cloth. Three specimens shall be cut in the direction of the warp, three in the direction of the weft and three on the bias at an angle of 45°. No two specimens cut in the same direction shall contain the same longitudinal threads.

The specimens shall be two inches wide and shall be placed evenly in the jaws of the testing machine so that the unstretched length of the cloth between the jaws is not less than 12 inches. The load shall be applied at a uniform rate and the time taken to reach the breaking load from the commencement of the application of the load shall be one minute. If the specimen breaks unevenly, or in or at the jaws, due to incorrect clamping, a duplicate test shall be carried out on another specimen including the same threads. The maximum, minimum and mean values of the three tests warp way, of the three tests weft way and of the three tests on the bias, respectively, shall be stated.

Tests shall be carried out at the following temperatures :—

20° C., 60° C., 90° C. and 120° C.

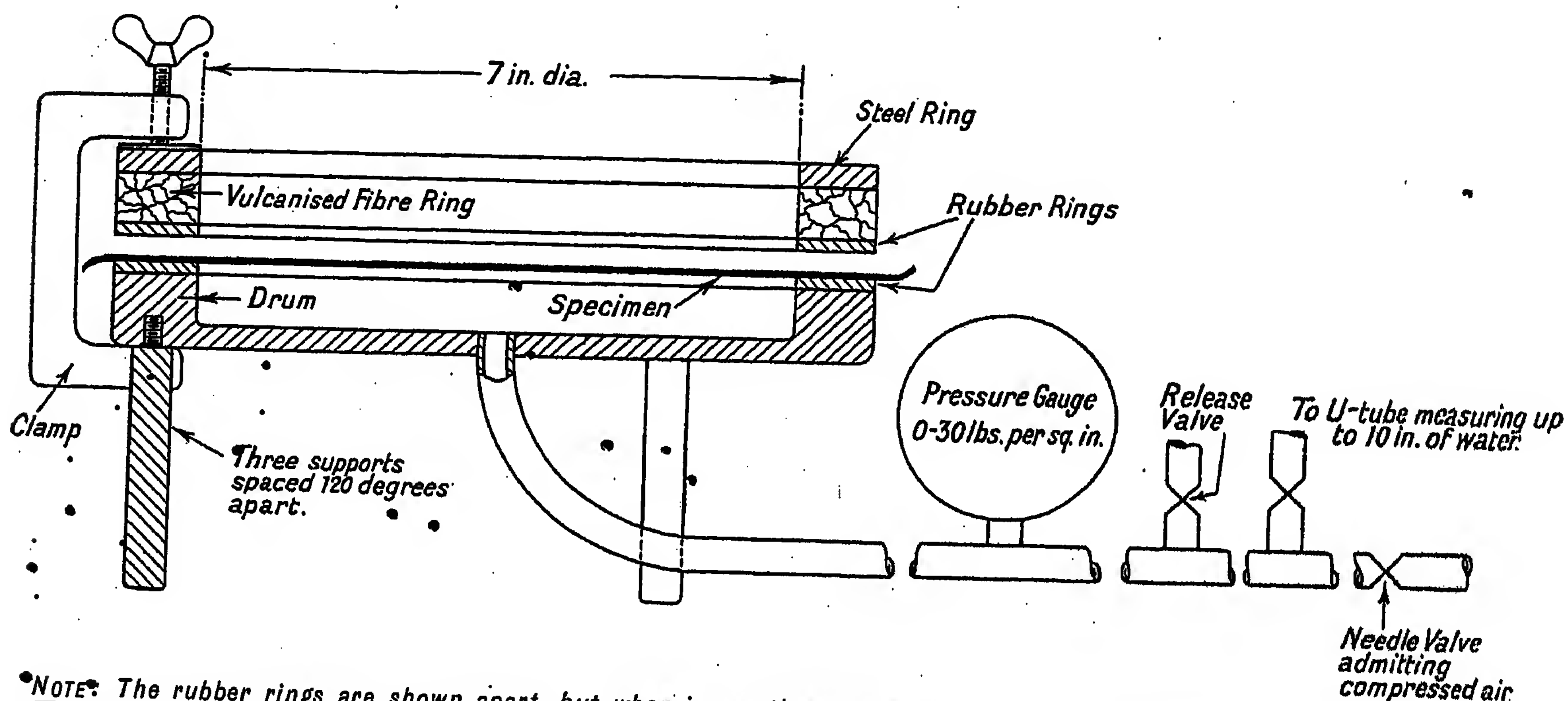
Note.—When testing at the high temperatures the specimen should be surrounded by a heated cylinder to maintain the required temperature.

13. Bursting Strength and Extensibility.

The bursting strength and extensibility shall be determined when the varnished cloth is in the Normal Condition as specified in Clause 9 (*a*).

The bursting strength test shall be carried out by means of the apparatus shown in Fig. 1 as follows :—

The varnished cloth shall be clamped between the



NOTE: *The rubber rings are shown apart, but when in use they are brought into contact with the specimen and fixed by clamps, one of which is shown in position.*

Fig. 1.—Apparatus for measuring the Bursting Strength of Varnished Cloth.

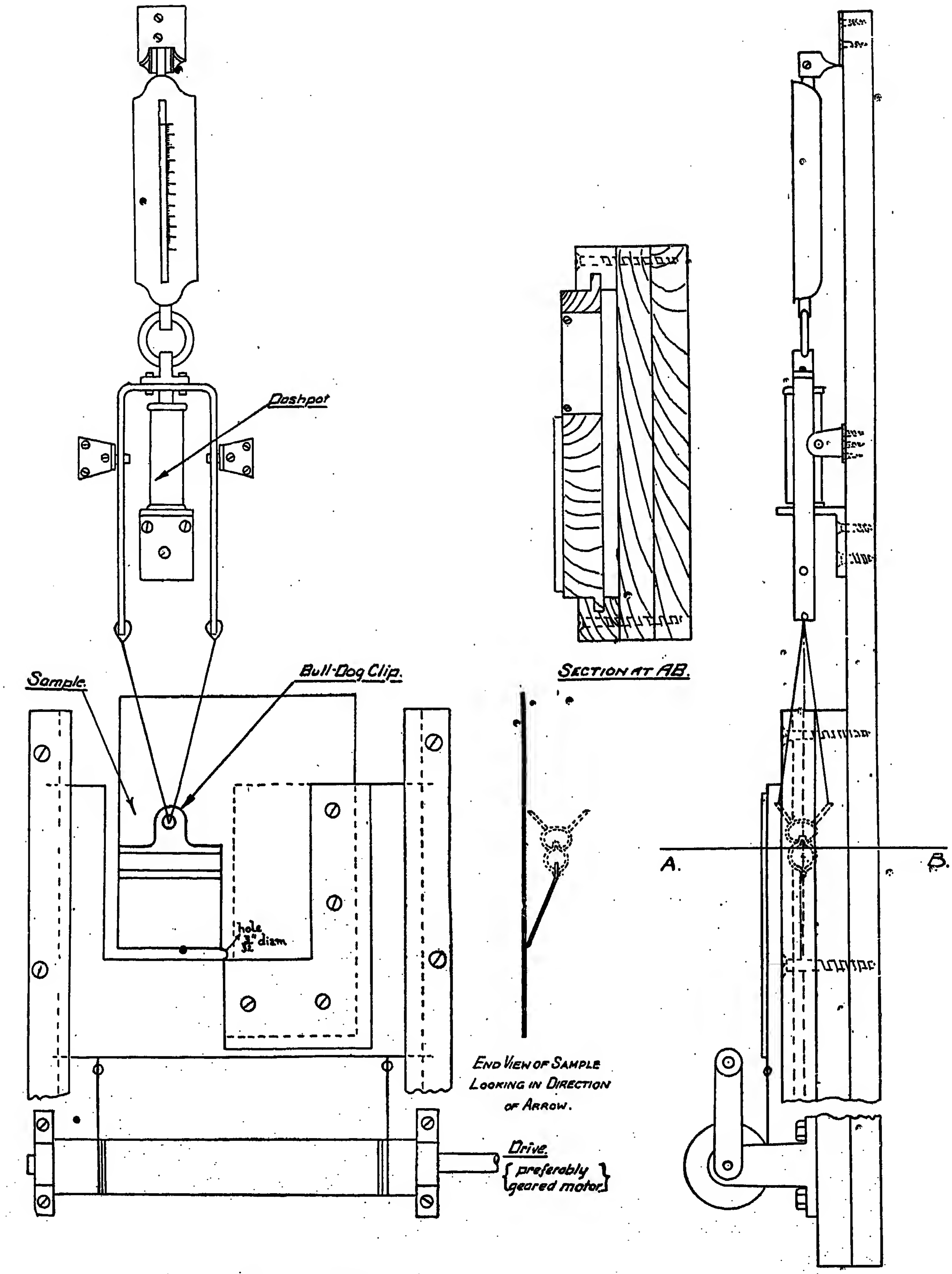


FIG. 2.—Apparatus for measuring the Tearing Strength of Varnished Cloth.

rubber insertion rings fitted on top of the drum so as to make an airtight joint. Air shall be pumped into the drum at such a rate that the pressure on the varnished cloth diaphragm is increased gradually at the rate of approximately 30 lb. per minute until failure occurs.

The test for extensibility shall be carried out on the apparatus shown in Fig. 1 as follows :—

The varnished cloth shall be clamped between the rubber rings as before. Air shall be pumped into the drum at such a rate that the radii of curvature of the varnished cloth diaphragm can be determined by means of a suitable spherometer. Sufficient readings shall be taken to enable a curve to be plotted showing the relationship between the air pressure and the radius of curvature of the diaphragm.

14. Tearing Strength.

The tearing strength shall be determined when the varnished cloth is in the Normal Condition as specified in Clause 9 (*a*).

The tearing strength test shall be carried out by means of the apparatus shown in Fig. 2 as follows :—

The resistance to tearing shall be proved by the load required to tear the varnished cloth commencing from a hole 3/32 inch diameter punched out of the cloth. The position of the hole and application of the load shall be as shown in Fig. 2.

The size of each separate specimen tested shall be 6 inches square.

(*a*) Three tests shall be made with the tear in the direction of the warp of the cloth. This shall be called the "Warp Tear Test."

(*b*) Three tests shall be made with the tear in the direction of the weft of the cloth. This shall be called the "Weft Tear Test."

The method of carrying out the tearing test shall be as follows :—

Prepare the varnished cloth specimen as shown in Fig. 2.

Swing the inverted L piece to the right.

Place the specimen in position, the punched hole being at the edge of the L piece as indicated.

Screw the L piece down. Bend over the cut piece and attach grip device—needle or clip—and secure to lower portion of balance.

Rotate the winding gear with steady movement at a rate of approximately 12 inches per minute until the 6-inch length is torn through. (A motor drive is recommended.)

Watch the balance and average the slightly varying values of the pull observed.

The maximum, minimum and mean values of the "warp" and "weft" tearing strengths respectively shall be stated.

15. Resistance of Varnish Film to Crushing.

The resistance of the varnish film to crushing shall be determined when the varnished cloth is in the Normal Condition as specified in Clause 9 (*a*).

The pressure required to damage the varnish film shall be ascertained by the following test, observation being made by visual inspection, assisted, if necessary, by a magnifying glass :—

The varnished cloth shall be compressed between a smooth metal plate and adjacent steel balls 1/8 inch diameter.

16. Ageing.

The tendency of the varnished cloth to deteriorate with age shall be determined by the change in the bursting strength after it has been heated at a temperature from 90° C. to 95° C. for four weeks.

Bursting strength tests shall be carried out as specified in Clause 13 as soon as the temperature of the specimen has fallen to 20° C. (± 5° C.), and also after the varnished cloth has been exposed to Normal Condition (Clause 9 (*a*)) for one week.

17. Resistance to Oil.

The varnished cloth shall be immersed in transformer oil, complying with British Standard Specification No. 148 for light grade oil, at a temperature from 115° C. to 120° C. for seven days, and the effect on the varnished film shall be stated.

18. Determination of Thickness.

The thickness of the varnished cloth shall be measured by means of a suitable micrometer.

Note.—In general, more reliable values of thickness can be obtained by measuring (say) 10 thicknesses and dividing the result by 10.

The average thickness of the varnished cloth shall be determined as follows :—

In the case of rolls, a test piece one foot long and the full width of the roll shall be taken sufficiently far from the end as to be representative of the bulk of the cloth. Ten measurements of thickness equally spaced diagonally across the test piece shall be made.

In the case of sheets, ten measurements of thickness equally spaced diagonally across the sheet shall be made.

The maximum, minimum and mean values of the thickness shall be stated.

19. Determination of Density.

The density shall be expressed in terms of weight in grammes per square metre. The varnished cloth shall be weighed in the Normal Condition as specified in Clause 9 (*a*).

DISCUSSION ON

"THE NATURE OF THE MAGNETIC FIELD PRODUCED BY THE STATOR OF A THREE-PHASE INDUCTION MOTOR." *

Dr. A. E. Clayton (*communicated*): The nature of the magnetic field produced by the armature windings of alternating-current machines is of importance, not merely in so far as it concerns induction motors, but with alternating-current machinery generally. It is not surprising, therefore, to find that the subject has attracted much attention during recent years.

Nomenclature.—The author raises the question—and it is important—of nomenclature. In this connection I have found it a great help, in dealing with all types of windings, to make use of the term "coil span" in cases where, apparently, the author would use "coil pitch." The term "coil pitch" may then be reserved to indicate the actual displacement between successive coils, the term thus having a meaning corresponding exactly to such terms as pole pitch, rivet pitch, and so on. Thus, for example, in the case of a commutator winding as in Fig. A, instead of using the terms "back

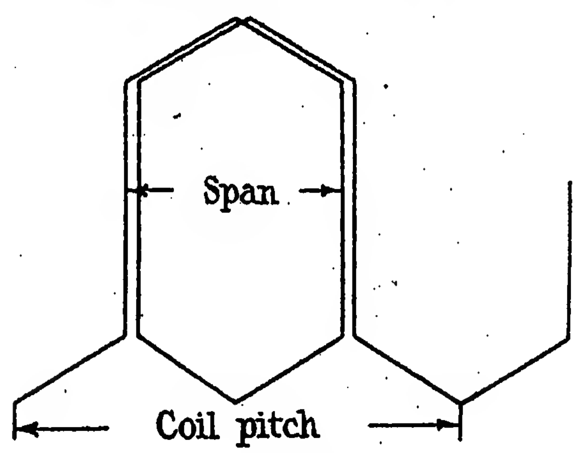


FIG. A.

pitch," "front pitch" and "total pitch," it only becomes necessary to use "coil span" and "coil pitch" as indicated in the figure. There is much to be said for this method, and as the effects of coil "span" and coil "pitch" are essentially different, it is a convenience to denote them by different terms. For example, with direct-current windings the pitch, as above defined, determines entirely the *type* of winding—simple lap, wave, etc. The coil span has no influence whatever upon the type of winding, but simply determines its suitability for any particular number of poles. This may be illustrated by the case of, say, a 39-slot, 4-pole, direct-current wave-wound armature having 117 commutator segments and armature coils. If the coil pitch, as above defined, is 58, the winding will form a two-circuit, simple wave winding for all values of the coil span, whether it be 8, 9, 10 or 11, etc., teeth. Incidentally, it may be noted that whereas it is necessary to express the coil pitch—or, what amounts to the same, the commutator pitch—in terms of the number of coils or commutator segments, the coil span is often best expressed as the number of teeth spanned by the coil. Similarly, with alternating-current windings it is the displacement between successive coils in the same series circuit which determines the nature of the winding. Thus, with 12 coils equally spaced around an armature and connected in series so as to carry current in the same direction, a 24-pole arrangement is formed quite irrespective of the value of the span—or, for that matter, of the spread—of the individual coils. The span of the coil simply determines the effectiveness of the coil for the particular number of poles for which the winding is suitable. To obtain maximum effect, the coil span must be an exact pole pitch, or some odd multiple of that amount. The term "full-pitch coil" has long been in use and, to my mind, is quite definite in indicating a coil which spans an exact pole pitch. In addition, to indicate a coil which does not span an exact pole pitch, the term "fractional-pitch coil" is much used; alternatively, the coil is often said to be "chorded." These terms all seem to me to be good, as they indicate definitely the feature characteristic of the coil. In the case of complete windings of the two-layer lattice type the terms "full-pitch winding" and "fractional-pitch winding" can at once be applied without any possibility of confusion to the cases where the individual coil spans an exact pole pitch or a fraction of the pole pitch, respectively. But with single-layer windings there is, as pointed out by the author, a possibility of confusion arising from the use of these terms in the case of windings of the "half-coiled" type, since the mean span of the component coils is then rather less than a pole pitch for the windings commonly referred to as "full-pitch." All difficulty can be removed if the winding is regarded as having a number of phases equal to the number of complete coils per pair of poles, as indeed is only logical. Thus a three-phase half-coiled winding is in reality a six-phase winding, and for the normal case of a concentric single-layer winding, the six-phase winding is slightly chorded. For analytical purposes I have found a great simplification to be possible by thus treating a winding having N coils per pair of poles as a symmetrical N-phase winding. But for normal commercial purposes it is naturally more convenient to regard a winding as having the same number of phases as the currents supplied to or by it, and it becomes necessary to consider the spacing of the actual conductors rather than the actual span of the component coils. Even in this case, however, I do not think that there is any difficulty in explaining what is meant by a full-pitch winding. A drawback to the use of the term "normal distribution" arises from the fact that it becomes necessary to explain what is meant by normal. If we regard the arrangement of the conductors in a twelve-phase, or a nine-

* Paper by Mr. F. J. Teago (see vol. 61, page 1087).

phase, or a six-phase synchronous converter as being normal, then that commonly used for three-phase machines must be regarded as abnormal. Or if the usual three-phase stator winding is regarded as normal, then all of the other cases must be considered to be abnormal. The term "super distribution" has, I think, but little to commend it, but that may be due to prejudice consequent upon the modern abuse of the word "super."

Reduction factor and chording factor.—The author correctly points out that the breadth factors in common use for E.M.F. calculations are numerically equal to the factors which he calls reduction factors for M.M.F. calculations. That being so, there appears to be no need to call them breadth factors in the one case and reduction factors in the other. I fail to see why the author, instead of evaluating the simple and well-known expression $(\sin \frac{1}{2}nm\psi)/(m \sin \frac{1}{2}n\psi)$, expresses the value of the coefficient as a series of cosines. When the number of slots per pole is large the waste of labour thereby caused is very considerable. With chorded windings it is simply necessary to introduce a chording factor numerically equal to the sine of half the angle spanned by the "coil," the angle being expressed in electrical measure to correspond to the particular harmonic under investigation.

Harmonics in supply current.—There are one or two minor points in the paper to which reference may be made. It is not quite correct to state, as on page 1087, that the harmonics are due to the windings being contained in slots; important higher harmonics will be present with surface windings. Again, in order that harmonics of the third order shall be absent from the resulting M.M.F., with a three-phase winding it is not necessary that the supply current shall be sinusoidal. These particular M.M.F. harmonics will disappear for all current wave-shapes other than those which contain harmonics of the third order.

Ratio of iron losses and magnetizing currents.—In comparing the performance of a particular induction motor as a 2-pole and as a 4-pole machine the author appears to omit one very important factor. He appears to neglect the effect of the armature core. As shown by the author, the ratio of the air-gap densities, neglecting leakage, for 4-pole and for 2-pole working is 1·46. This ratio is not in itself a complete criterion. It is necessary also to consider the ratio of the actual total flux per pole for 4-pole and for 2-pole working. In spite of the reduced air-gap density, the flux per pole with 2-pole connections will be 1·37 times as great as for 4-pole working. The relative values of the magnetizing current, and of the iron losses, for the two methods of connection will therefore depend entirely upon the degree of saturation in the teeth and in the core, and approximations which omit the effect of the core are not likely to be of much value.

Crawling.—In connection with Section 6 of the paper, it is perfectly true that saturation will cause increased fringing and round off the corners of the steps in the M.M.F. wave. Whether this will cause a reduced tendency to crawl depends entirely upon the number of slots per pole, as the spacing ripple harmonics may not be of orders likely to cause crawling. In the great majority of cases these ripple harmonics are of much higher orders than would cause trouble. On the other hand, saturation may introduce into the field form harmonics of low orders, which are quite unimportant in the unsaturated condition. For the case cited by the author, the evidence quoted in the paper fails to support his view that crawling on 2-pole connections is due to the reduction in the flux density in the air-gap. For he states that there is no tendency to crawl with 4-pole connections at half normal voltage. Under these latter conditions the flux density in the gap is much less than with 2-pole connections. With 2-pole connections crawling would appear to be due to the fact that the seventh harmonic in the M.M.F. distribution is far more pronounced than with 4-pole connections. On pages 1092 and 1094 the author appears to imply that crawling may be established by the fifth harmonic in the M.M.F. distribution, and suggests that it may be desirable to eliminate the effects of this particular harmonic. It does not seem to me that any tendency to crawl will be established by the fifth harmonic, for the resulting M.M.F. due to this particular harmonic rotates in an opposite direction to that due to the fundamental. As a result there will be a small braking action due to this harmonic, decreasing slightly as the motor speeds up, but it does not appear to me that there will be any tendency for the fifth harmonic to establish a definite crawling speed. The seventh harmonic gives rise to a field rotating in the same direction as the fundamental, and causes a pronounced "ripple" to occur in the graph representing the running-up torque plotted in terms of the speed. The crest of this ripple occurs at a speed rather less than one-seventh of normal synchronism, and the trough at a speed somewhat higher than this amount. Normally, the speed at which the motor may crawl will then be slightly in excess of one-seventh of synchronous speed. With two-phase machines, trouble may be expected from the fifth harmonic, as in this case the corresponding resulting field rotates in the same direction as that due to the fundamental.

Mr. F. J. Teago (*in reply*):

Nomenclature.—I quite agree with Dr. Clayton that it would have been better if I had used the term "coil span" rather than "coil pitch," because, as he points out, coil pitch is a most appropriate name for what is usually termed "coil creep." I do not, however, agree that full pitch, fractional pitch, chorded, etc., are definite terms, for the following reason: Alterations in the pitch, or span as it should be called, are made for very definite reasons and if such alterations fail to produce the desired results then the alterations in the span are not real. In alternating-current work, short spans are mainly used to eliminate harmonics. Figs. 4 and 7 (single and two-layer windings respectively) in my paper have, by all appearances, the right to be called short span, since the two sides of any one coil do not span one pole pitch, but with regard to the harmonics they produce in their M.M.F. curves they are identical with full-span coils. The problem then is what to call them. Geometrically they are short span. Electrically they are full span. I have tried to compromise by calling both normally distributed windings.

This suits both admirably, since "normal" distribution is one in which no slots containing conductors of any other phase are introduced between the slots containing the conductors of the phase under consideration. As Dr. Clayton points out, the terms "normal" distribution and "super" distribution may not be suitable for all classes of machinery, but for open-coil windings such as are used on alternators and induction motors they appear to have much to recommend them. Whatever the span of the coils, there is no change electrically from full-span coils unless the span is such as to cause the distribution to change from "normal" to "super."

Reduction factor.—I do not necessarily intend to imply that the expression $(\sin \frac{1}{2}nm\psi)/(m \sin \frac{1}{2}n\psi)$ should always be evaluated from its component parts (Table 1), but to be able to express any formula in its component parts is invaluable when one wants to ascertain the effect of a departure from the normal. Thus the component parts of the expression for any winding scheme of the types described can be readily written down as a trigonometrical series; some are given on pages 1092 and 1093, and have the advantage that the chording factor, as Dr. Clayton describes it, will be included.

Chording factor.—Dr. Clayton's remark, that the chording factor is numerically equal to the sine of half the electrical angle spanned by the coil, wants qualifying. Provided that the span alters the distribution and in the case of the two larger windings in Figs. 8 and 9, it is true, but occasionally the sign as well as the magnitude is required to be correct, so that it is much

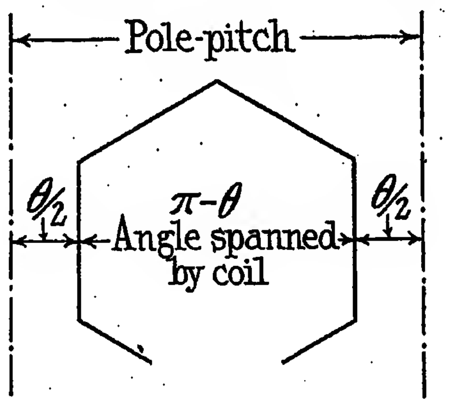


FIG. B.

better to use $\cos \frac{1}{2}n\theta$ than $\sin \frac{1}{2}n(\pi - \theta)$ (see Fig. B). For $n = 7$ and Fig. 9 (page 1091)

$$\cos \tfrac{1}{2}n\theta = \cos 210° = -\ 0{\cdot}866$$
$$\cos \tfrac{1}{2}\sigma n\psi = \cos 210° = -\ 0{\cdot}866$$
$$\sin \tfrac{1}{2}n(\pi - \theta) = \sin 420° = +\ 0{\cdot}866$$

This latter one is evidently wrong for sign. (See also Table 4, where the chording factor for the seventh harmonic is evidently negative.)

However, the expression $\cos \frac{1}{2}\sigma n\psi$, which I have suggested is correct both for sign and magnitude, also has the advantage that no mistake is likely to be made with windings which are apparently short span but not really so, since in these cases there is no super distribution, so that σ = zero and the chording factor $= 1{\cdot}0$. In the case of single-layer windings the chording factor is not, either in sign or magnitude, equal to the sine of half the electrical angle spanned by the coil. It is given by $(\cos \frac{1}{2}n\theta)/(\cos \frac{1}{2}n\psi)$ and is affected by both the span of the coil and the angle between successive slots. It is also given by $[\cos (\xi + 1)\frac{1}{2}n\psi]/(\cos \frac{1}{2}n\psi)$. This form, again, is not likely to cause mistakes, since where there is no super distribution ξ = zero and the chording factor $= 1{\cdot}0$.

Harmonics in supply current.—I quite agree with Dr. Clayton that harmonics would be present even with a surface winding, but this does not make my statement incorrect; it merely broadens it. Dr. Clayton is also quite correct in pointing out that, in reality, only the third harmonic need be absent from the supply current in order to suppress the third harmonic in the M.M.F. curve, but, again, this only broadens my statement. My chief aim is to prevent the idea that the supply current is producing the particular harmonics under consideration. However, if harmonics are present in the supply current then the system of waves of M.M.F. may contain stationary as well as rotating components of a complex character, the effect of which has not been included within the scope of the present paper.

Ratio of iron losses and magnetizing currents.—Dr. Clayton has evidently misread page 1095. I have not attempted to imply that if $\beta_4/\beta_2 = 1{\cdot}46$ then the ratio W_4/W_2 should be expected to equal $1{\cdot}46$, but for some reason is equal to $1{\cdot}6$. If $\beta_4/\beta_2 = 1{\cdot}46$, then the corresponding value of W_4/W_2 obviously depends upon the actual values of β_4 and β_2, since the curve connecting iron loss and β is not linear. I do not know the actual values of β_4 and β_2, but from iron-loss curves and probable values of the densities, I should have expected W_4/W_2 to be greater than $1{\cdot}6$. In obtaining the ratio of the magnetizing currents, I think Dr. Clayton must admit that I have at least made some allowance for the core and not neglected it as he suggests. My percentage allowances may not be strictly correct, but they are of the order one would expect, knowing the ratio β_4/β_2 and the probable, but not the actual, values of β_4 and β_2.

Flux density and crawling.—At half normal voltage, with the 4-pole connection, the density in the gap is $0{\cdot}73$ times that with full voltage and the 2-pole connection, so that if the reduction factors in Table 5 are assumed to be correct for the 4-pole case, they are on the high side for the 2-pole case; but the lower the density in the 2-pole case the more nearly are they correct. The crux of the matter is not the ratio of the gap densities but whether the density in the 2-pole case is low enough to cause the reduction factors to be sensibly as set out in Table 5.

Fifth harmonic.—I do not mean to imply that the fifth harmonic will establish a definite crawling speed, but the fifth harmonic has an influence on the tendency of the motor to crawl, as has been pointed out by Prof. J. K. Catterson-Smith in the paper referred to at the foot of page 1088. In conclusion, I am indebted to Dr. Clayton for his criticism, since it is apparent that parts of the paper have been so condensed that wrong conclusions may be drawn from the text, and it is only by the valuable aid of those who are prepared to study a paper in detail that the doubtful points are cleared up.

PERIODIC TRIGGER RECEPTION.

By E. V. Appleton, M.A., D.Sc., and F. S. Thompson, B.A., Royal Corps of Signals.

(*Paper received 26th September, and read before the* Wireless Section *21st November*, 1923.)

Summary.

The phenomenon of oscillation hysteresis exhibited by simple triode generators is discussed theoretically. A practical method of reception in which this phenomenon is utilized in a periodic manner is described. This method, which for convenience may be termed "periodic trigger reception," is suitable for continuous-wave and spark signals.

A low-frequency electromotive force is introduced in the grid circuit of a simple triode oscillator in such a way that high-frequency oscillations are not produced in the absence of an incoming signal. A small signal of high frequency is, however, sufficient to produce a train of free oscillations once every low-frequency cycle. Such free oscillations are rectified by the triode, and a signal of the impressed low frequency is heard in the receiver telephones.

The system differs fundamentally from the Armstrong super-regenerative receiver in the following respects:—

(*a*) The ordinary oscillation-hysteresis characteristic is followed in a "quasi-stationary" manner;

(*b*) No self-oscillations are produced in the system in the absence of an incoming signal; and

(*c*) The amplitude of the telephone signal is practically independent of the amplitude of the incoming signal and not proportional to it as in super-regenerative receivers.

It has been discovered experimentally that oscillations may be maintained in a simple triode generator with extreme negative grid potentials such as would cut off the anode current entirely under normal conditions. A simple theory for the conditions necessary for such maintenance is given. An oscillator of this type is very efficient in that anode and grid currents are only permitted to flow for a very small part of the cycle.

It is now becoming more and more generally recognized that, in order to account satisfactorily for the behaviour of many modern wireless circuits, proper account must be taken of the non-uniform conductances of the triodes used. Indeed, in many cases, no explanation at all, however approximate, is possible unless the non-linear nature of the triode characteristics is recognized. Various examples of this may be mentioned. Some time ago Dr. van der Pol and one of the present authors * found that, for a triode generator, there was often a pronounced difference between the limiting conditions for the starting and stopping of free oscillations. This difference was accounted for by the peculiar shape of the triode characteristics for the particular conditions used. An explanation of such a phenomenon in terms of straight characteristics is obviously impossible. The non-linear theory was also applied by Dr. van der Pol † to account for the discontinuities in phase and frequency which are encountered in coupled-circuit transmitters. Later one of the present authors * showed how a similar theory accounted for the main features of the synchronization phenomena met with when two triode assemblies with mutual interaction are adjusted so as to be nearly in resonance.

The above examples are cases of free oscillations, but similar phenomena are met with in cases of forced oscillations. For example, in continuous-wave reception by the auto-heterodyne method it is very often noted that there is a "silent interval" of receiver frequency in the region of resonance, within which no signal is heard. Such a phenomenon has been explained † in terms of the non-linear characteristics of the triode, and it has been shown that in such a case the presence of forced vibrations of amplitude greater than a certain critical value, due to the signal, automatically suppress the free vibration so that no beats occur and no combination tone is heard in the receiver telephone. Another interesting example of forced vibrations in a non-linear system has recently been described by E. H. Armstrong,‡ who has shown that a triode assembly may often be made more sensitive as a receiver of high-frequency oscillations if there is present in the system another forced vibration of quite different and uncorrelated frequency. In attempting to explain the action of the circuits described by Armstrong, one of the present authors found a non-linear triode system in which the interaction of the forced vibrations is such that the amplitude of one vibration is increased by the presence of the other, and it is with this scheme that the present paper deals. At first the mistake was made of concluding that such a scheme was necessarily the same as Armstrong's, but a practical investigation of the method (which for convenience may be termed the "periodic trigger" method), together with a closer examination of Armstrong's super-regenerative circuits, has shown that, while both methods depend on the interaction of two forced vibrations, there are many essential and fundamental differences between them. Such differences will be mentioned later in the paper.

The method of reception to be described is based on the difference (mentioned above) between the conditions for the building up of triode oscillations from an infinitesimally small amplitude and the conditions for the maintenance of an oscillation already existing. In this respect it is somewhat analogous to the trigger

* Appleton and van der Pol: *Philosophical Magazine*, 1922, vol. 43, ser. 6, p. 177.
† van der Pol: *ibid.*, p. 700.

* Appleton: *Proceedings of the Cambridge Philosophical Society*, 1922, vol. 21, pt. 3, p. 231.
† Appleton: *ibid.*, p. 233.
‡ Armstrong: *Proceedings of the Institute of Radio Engineers*, 1922, vol. 10, p. 244.

relay described by L. B. Turner.* We shall therefore preface our account of some of the practical points connected with the working of this method with a short theoretical account of the fundamental points underlying trigger action in general.

Let us consider the case of the simple oscillator circuit shown in Fig. 1. For this circuit it is well known that, if the mutual inductance M between the coils L_1 and L_2 is of the correct sense, and is gradually increased from a low value, oscillations are spontaneously produced when M reaches a certain critical value. This value is given by the equation †

$$aM = -\left(RC_1 + \frac{bM^2}{L_1}\right) \quad . \quad . \quad . \quad . \quad (1)$$

where R and C_1 are respectively the resistance and capacity of the oscillatory circuit, and a and b are respectively the mutual conductance and the anode conductance of the triode. In most practical cases the second term on the right-hand side of Equation (1) is small compared with the first, so that the numerical critical value of the mutual inductance is given by

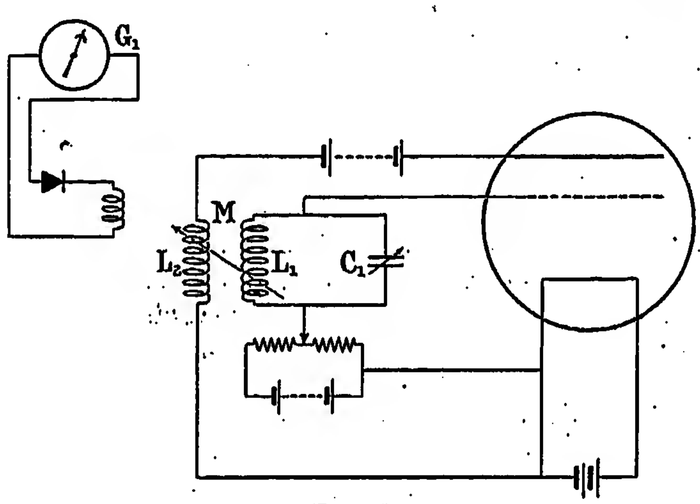


Fig. 1.

$$M = \frac{RC_1}{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Let us now consider the effect of varying the steady grid potential of the oscillator by means of the potentiometer shown in Fig. 1, and, in connection with this, let us imagine that the foot of the grid-voltage/anode-current characteristic of the triode is as illustrated in Fig. 2.

It is clear that oscillations will not start if the representative point of grid potential is to the left of − 8 volts, in which case no anode current flows. Oscillations are, however, spontaneously produced if the representative point is moved to the right of this value to a point such that the slope of the curve is equal to a, as defined by Equation (2). We thus know precisely the conditions for the starting of oscillations.

Let us now assume that the representative point is fixed first at − 20 volts by means of the potentiometer, and, further, let us assume that a large oscillation is temporarily induced in the oscillator so that the representative point now oscillates for a few periods about its new zero. It is clear that the induced oscillations will not be maintained if this induced voltage is insufficient to take the representative point into the region of finite anode current. But if the oscillatory grid potential is of sufficiently large amplitude, such as is illustrated by the sine curve below the characteristic shown in Fig. 2, there is the possibility that the anode current-changes may be such as to assist in maintaining the oscillations with constant amplitude. The conditions for this may be stated fairly precisely.

Let the induced oscillatory grid potential v be expressed by $v = A \sin \omega t$, where $\omega^2 = 1/(L_1C_1)$ (see Figs. 1 and 2). Then once every cycle the anode current will flow for a time. Let the fundamental component of these periodic anode-current changes be represented by ${}_1i_a$. Such an alternating component of anode current will produce by induction via M an electromotive force of magnitude $M\omega{}_1i_a$ in the oscillatory circuit. This electromotive force acting at resonance

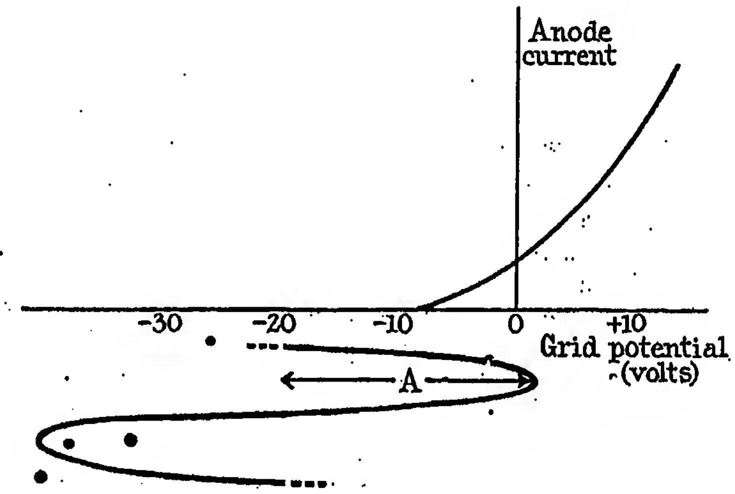


Fig. 2.

on the oscillatory circuit L_1C_1 (see Fig. 1) will, in itself, produce an alternating grid potential of maximum amplitude $M{}_1i_a/(RC_1)$, and a little consideration shows that this amplitude is in phase with the original grid potential-changes if M is of negative sign. We thus see that the oscillation of amplitude A is maintained if the result is equal to the cause, or if

$$A = \frac{M{}_1i_a}{RC_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The above explanation may perhaps be put a little more precisely as follows. With reference to Fig. 1 let us assume that Q is the charge on the oscillatory circuit condenser at any instant. We then have, as the expression of the electromotive forces in the circuit,

$$L_1\frac{d^2Q}{dt^2} + R\frac{dQ}{dt} + \frac{Q}{C_1} = -M\frac{di_a}{dt} \quad . \quad . \quad (4)$$

where i_a is the anode current and t is the time. Let us now write *

$$i_a = \phi(v) = \phi\left(\frac{Q}{C_1}\right) = av + \beta v^2 + \gamma v^3 + \delta v^4 + \epsilon v^5 \quad (5)$$

* British Patent No. 130408.

† Appleton: *Philosophical Magazine*, 1919, vol. 37, p. 134; and *Proceedings of the Physical Society*, 1921, vol. 33, pt. 2.

* We have here assumed, for simplicity, that the anode current is mainly controlled by the grid potential, and we have thus neglected the effect of change of anode potential due to induction between the coils L_1 and L_2 in Fig. 1.

where v is the departure of the grid potential from its stationary value and α, β, etc., are constants. Equation (4) thus becomes

$$\frac{d^2v}{dt^2}+\left[\frac{R}{L_1}+\frac{M\phi'(v)}{L_1C_1}\right]\frac{dv}{dt}+\omega^2v=0 \quad . \quad . \quad (6)$$

where ω^2 has been written for $1/(C_1L_1)$.

An approximate solution of an equation similar to (6) has been previously given,* so that only the final results of the solution need be stated here.

It may be shown that, if M is of negative sign and a solution of the type $v=a\sin\omega t$ is assumed, the possible stationary amplitudes are given by the real roots of

$$\left(\frac{RC_1}{M}-\alpha\right)a^2-\tfrac{3}{4}\gamma a^4-\tfrac{5}{8}\epsilon a^6=0 \quad . \quad . \quad (7)$$

These roots may be written

$$a_1^2=0$$

$$a_2^2=-P-\sqrt{(P^2-N)}$$

and $$a_3^2=-P+\sqrt{(P^2-N)}$$

where $P=\frac{3}{5}\gamma/\epsilon$ and $N=-(8/5\epsilon)[(RC_1/M)-\alpha]$, and the square roots are taken as having a positive real part. But such amplitudes, though possible, are not necessarily stable, and a criterion of stability is necessary for each of the three amplitudes given by (7).† These are respectively:—

$$\text{For } a_1;\ \left(\frac{RC_1}{M}-\alpha\right)>0$$

$$\text{For } a_2;\qquad \epsilon a_2^2>0$$

$$\text{For } a_3;\qquad -\epsilon a_3^2>0$$

We thus see that if $[(RC_1/M)-\alpha]$ and γ are positive and ϵ is negative,‡ oscillation hysteresis is possible in that the zero amplitude, a_1, is stable, as is also the finite amplitude a_3, while between the two an unstable amplitude of value a_2 is to be found. This unstable amplitude is really the "threshold" value, in that a temporarily induced amplitude greater than this value will automatically build up to the stable value a_3. One less than this value will finally reach the stable zero value a_1. The triode system is thus in a stable condition when not oscillating and when oscillating with amplitude a_3.

We thus see that the whole question of oscillation hysteresis and trigger action is definitely attributable to the shape of the triode characteristic and is not dependent on the presence of gaseous ionization in the triode, as has sometimes been supposed.

The relation between the above theoretical considerations and the practical working of the proposed method of reception may best be illustrated by what, for convenience, may be termed the oscillation-hysteresis (or "backlash") characteristic of a simple triode oscillator. This is obtained by plotting the relation between the current in the oscillatory circuit and the grid potential as controlled by a grid potentiometer. The circuit used for determining this relation is shown in Fig. 1, while a typical example of the results obtained for a standard "R" triode is exhibited in Fig. 3 (a).

The circuit of Fig. 1 is seen to be a simple oscillator to which is weakly coupled a detecting coil in series with a crystal detector and sensitive galvanometer, G_1. The grid potential is continuously variable by means of a potentiometer consisting of cells and a non-inductive resistance, and is calculable from a knowledge of the resistance and the grid battery voltage. The relation between the galvanometer readings (which are proportional to the square of the oscillatory current) and the grid potential is shown in Fig. 3 (a) together with the ordinary grid-potential/anode-current characteristic of the triode. It will be seen that on starting with a large negative grid potential (e.g. -35 volts) and reducing this gradually, oscillations do not start

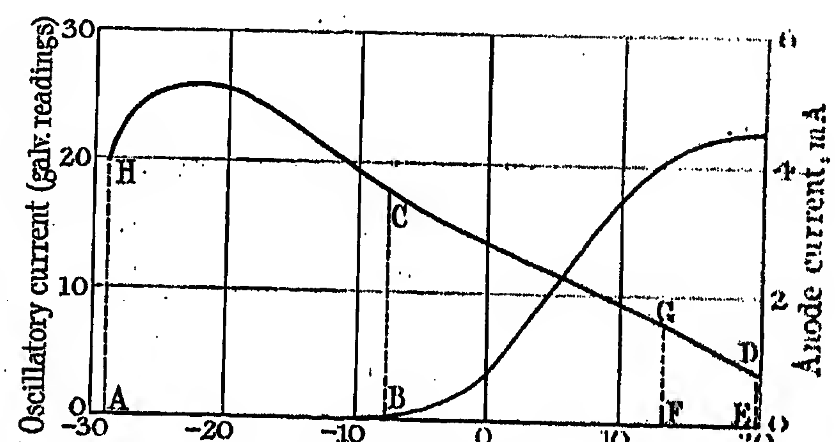


FIG. 3 (a).

until conditions represented by the foot of the ordinary static characteristic are reached (e.g. at $-7\cdot8$ volts), when an oscillation suddenly starts. Reducing the negative grid potential to zero causes this high-frequency oscillation to diminish somewhat in amplitude, but the grid potential must be increased to $+20$ volts before the oscillation finally and suddenly ceases. On now retracing these grid potential-changes the system remains in the non-oscillating condition until the grid potential becomes $+13\cdot2$ volts, when oscillations suddenly start again. On reducing the potential still further the old part of the curve is retraced, but now the grid potential must be made -29 volts before the oscillations can be finally stopped. In other words, if a continuous variation of grid potential is made from -30 volts to $+30$ volts and back again, two oscillation-hysteresis loops are obtained, the variation of oscillatory current being illustrated by the path ABCGDEFGCHA in Fig. 3 (a). The magnitudes of the positive and negative backlash regions [FE and AB in Fig. 3 (a)] are further illustrated in Fig. 3 (b), where the relation between these quantities and the back-coupling, M, is shown. We thus notice the remarkable fact that oscillations, if once started, can be maintained with strong negative grid potentials for

* APPLETON and VAN DER POL: *loc. cit.*, p. 179. For a more accurate treatment of this equation see APPLETON and GREAVES: *Philosophical Magazine*, 1923, vol. 45, p. 411.

† APPLETON and VAN DER POL: *loc. cit.*, p. 183.

‡ It is easily seen that if we are working at conditions represented by the foot of the characteristic, and M is less numerically than the critical value, these conditions are usually fulfilled.

conditions represented by a region well to the left of the foot of the ordinary static characteristic. It is this region that we propose to utilize in a periodic manner for the reception of wireless signals. This discovery of the possibility of the maintenance of oscillations with extreme grid potentials (i.e. with potentials more negative than that required to cut off the anode current under normal conditions) leads to an understanding of the method of obtaining high efficiencies in a triode

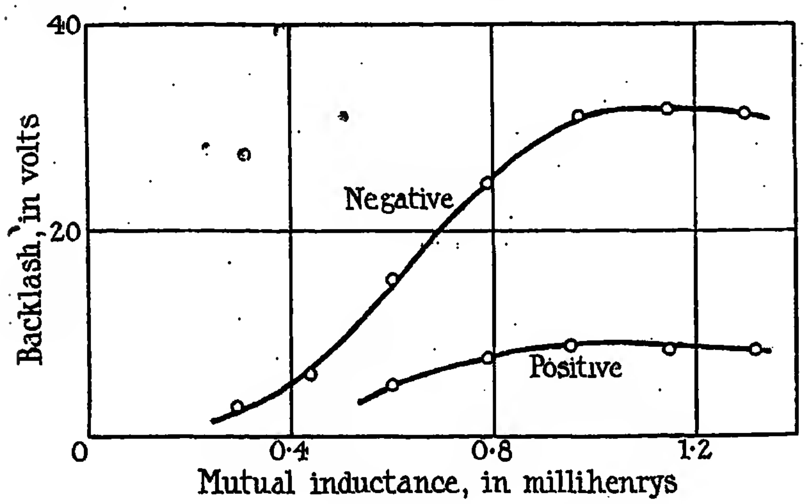


FIG. 3 (*b*).

transmitter, for in such cases the anode and grid currents flow only for part of the cycle. From the theoretical treatment given above we see that in the region represented by ABCH in Fig. 4, which represents the left-hand side of Fig. 3 (*a*), there are two stable states of the system, one quiescent (of amplitude zero) and the other oscillating (of amplitude given by the values HC). To make the system pass from the quiescent to the oscillating condition, oscillations have temporarily to be produced in the system of an amplitude greater

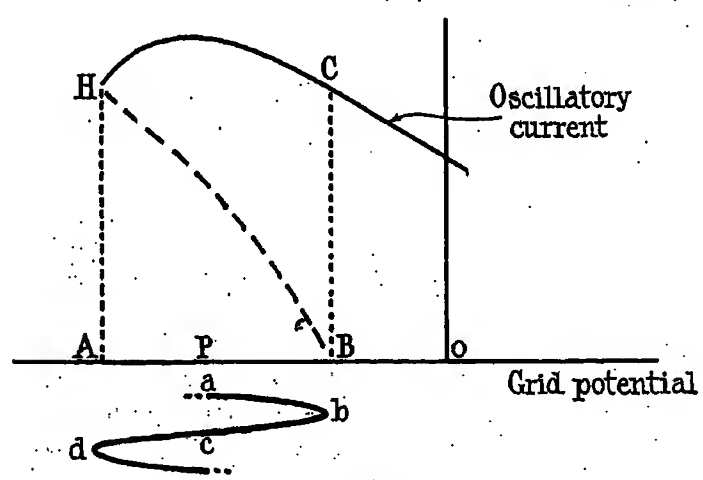


FIG. 4.

than the value indicated by the appropriate point on the broken line HB of Fig. 4, which represents the intermediate unstable values. Moreover, the amplitude of oscillations necessary to produce this trigger action is smaller the nearer we make the grid potential approach the point B from the left.*

Let us now consider the grid potential fixed at P and a cyclic potential of low frequency and of amplitude "ab" to be impressed about this point. A small high-frequency electromotive force impressed on the oscillatory circuit will now "trig" the system during the favourable conditions in the positive half of the low-frequency cycle (indicated by the point "b" in the figure) and the resulting oscillations will be maintained until the peak value of the other half-cycle (indicated by the point "d" in the figure) is approximately reached. The high-frequency oscillations thus produced in the triode system are rectified in the usual way, due to the curvature of the anode current characteristic, and a note of the impressed low-frequency cycle is heard in a telephone inserted in the anode circuit. In the absence of a high-frequency signal the system is not "trigged," and only a very feeble sound of the local low frequency is heard in the telephones. We thus have a method of receiving wireless signals based on periodic trigger action, the receiver being "trigged" by any signal strong enough to take the system over the threshold in the favourable parts of the low-frequency cycle.

In the cycle of operations indicated by Fig. 3 (*a*) the grid voltage-changes must be sufficiently slow to enable the oscillatory amplitude to reach its limiting value for the appropriate conditions. We may conveniently term such grid potential-changes "quasi-stationary." In order that the results obtained with a cyclic grid potential should be interpretable in terms of the above characteristic, the cycle "abcd" of Fig. 4 must also be sufficiently slow as to be "quasi-stationary." Experimentally we have found that the higher the radio-frequency used, the higher may be the impressed low frequency consistent with the above condition. Further mention of this point will be made later.

In testing some of the fundamental properties of this method of reception we have used a 90-period impressed low-frequency grid potential obtained from the Cambridge town supply. This was introduced into the grid circuit by means of a transformer as illustrated in Fig. 5. Here L_1C_1 is the main oscillatory circuit coupled to the anode circuit by means of the coil L_2. The town supply of 100 volts was transformed to 40 volts and then introduced by magnetic coupling into the grid coil L_3. The last-named coil had to be shunted by a condenser C_2 of about 1 200 $\mu\mu F$, which acted as a high-frequency by-pass.

The oscillatory current in L_1C_1 was indicated by the loosely coupled detector-galvanometer circuit, while the telephone signals were detected aurally by the telephone or measured by the detector-galvanometer G_2. The high-frequency signal was provided either by a small triode set a few metres away or by the signals of GLA from Ongar. Both signals were faintly audible (no aerial being used) when the receiver was made to function as an auto-heterodyne set.

In adjusting the receiver for periodic trigger reception the grid potential was adjusted to a value slightly more negative than the value corresponding to the centre of the negative "backlash" region. The magnitude of the cyclic grid potential was increased by increasing the coupling M_2 until, in the absence of signals, a very loud note of the impressed low frequency was heard. The coupling was then diminished until the loud note just disappeared. For these conditions it is obvious

* Note that the curves AB, HB and HC represent the three roots a_1, a_2 and a_3 of Equation (7).

that the cyclic variation just fails to reach the critical starting grid voltage, and thus the system is quiescent over the whole of the cycle. In the presence of a high-frequency signal of sufficient magnitude, however, the oscillator is "trigged" every cycle, and the system oscillates during the whole of the right-to-left transit of the representative point. It is evidently advantageous to make this oscillation occupy as large a portion of the cycle as possible. The best results are therefore obtained with a cyclic grid potential equal to about half the "backlash" voltage. Moreover, this is the minimum cyclic grid voltage with which the alternate trigging and quenching can be carried out as required in this method.

In the presence of a high-frequency signal the note heard with the above circuit was very loud and audible a few yards from a pair of low-resistance Brown telephones. The cessation of either the high-frequency input (incoming signal) or the low-frequency input (cyclic grid potential) stopped the loud signal entirely. Thus the loud signal must be regarded as the product of the interaction of two forced vibrations in the non-linear triode system.

With the above apparatus a study was made of the dependence of the telephone signal current on

(a) The amplitude of the incoming signal at resonance;
(b) The frequency of an incoming signal of constant magnitude; and
(c) The back-coupling of the receiver.

The relation between the signal telephone current as measured in G_2 (Fig. 5) and the oscillatory current in the transmitter as measured by a loosely coupled detector circuit, is shown in Fig. 6. It is there seen that the telephone signal is practically independent of the incoming signal. Such a relation is to be expected from the theory given above if we assume that the signal necessary to "trig" the receiver is small compared with the self-oscillation of the receiver when trigged. Still further confirmation of this view is afforded by the observation that the telephone received signal was practically the same when the cyclic grid potential was increased until periodic trigger action took place automatically in the absence of an incoming signal.

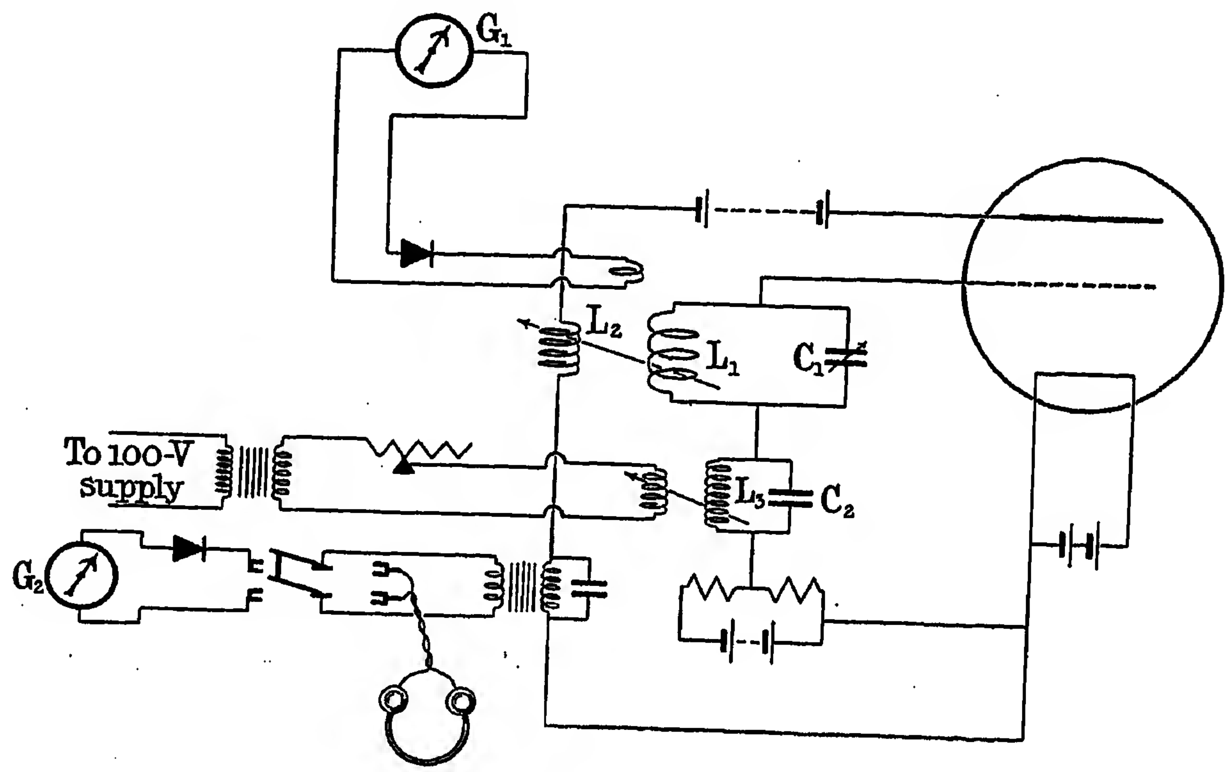


Fig. 5.

These observations show quite definitely the difference between periodic trigger action and the super-regeneration of Armstrong. In the first case the resulting telephone signal is practically independent of the amplitude of the incoming signal, whereas in super-regeneration, according to Armstrong,* "the free oscillations which are set up during the periods of negative resistance are directly proportional to the amplitude of the impressed E.M.F." Moreover, in periodic trigger reception there is no self-oscillation in the absence of a signal, whereas in super-regeneration there is always, according to Armstrong's oscillograms,†

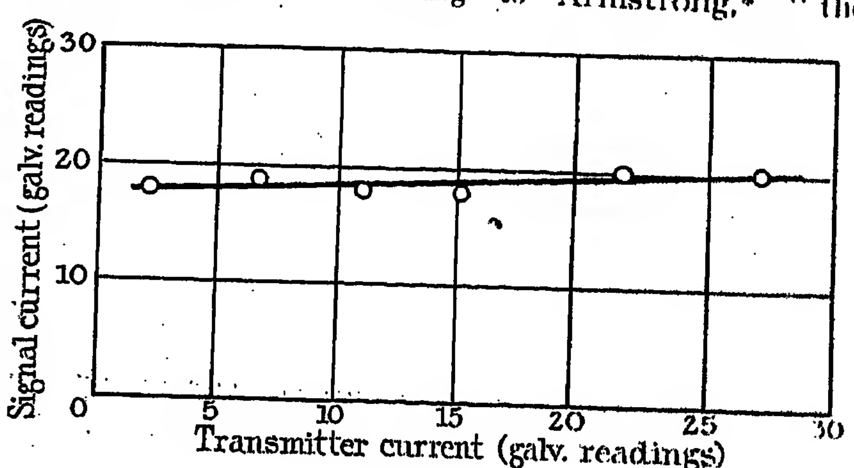


Fig. 6.

* Armstrong: *Proceedings of the Institute of Radio Engineers*, 1922, vol. 10, p. 244.

† Armstrong: *ibid.*, pp. 251 and 252.

a small self-oscillation in the absence of signals, which is enhanced by the signal.

The relation between the telephone current and the frequency of the incoming signal is illustrated in Fig. 7, where the galvanometer readings of G_2 are plotted as a function of the transmitter condenser readings. The transmitter amplitude was tested separately and found to be independent of the above-mentioned capacity alterations.

We again note that there is only a small alteration in the telephone current for these frequency changes. The telephone signal was found to start and stop abruptly at critical condenser values as the capacity was altered. There was not the slightest evidence of a gradual increase of signal strength from zero with gradual alteration of transmitter frequency, as is usual in ordinary receivers.

The strength of the telephone signal obviously depends on the magnitude of the high-frequency self-

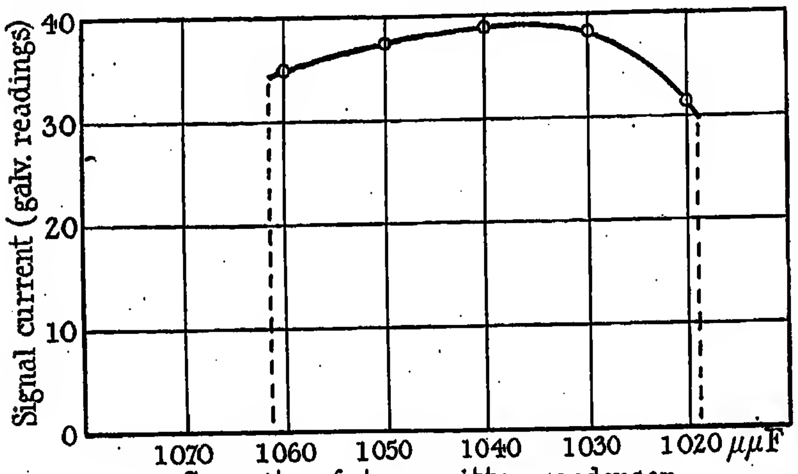


Fig. 7.

oscillations produced by the "trigger" action of the incoming signal. Thus any alteration made in the triode oscillator system which increases the amplitude of the self-oscillations (the detecting properties of the system being retained the same) will increase the telephone signal. This point is illustrated by some observations made on the effect of increasing the value of the mutual inductance on (1), the magnitude of the self-oscillation, and (2), the magnitude of the telephone signal in periodic trigger reception. In each case of (2) the cyclic grid potential was made approximately equal to half the "backlash" voltage, so that self-oscillations occupied half the cycle. The results are set out in Table 1. From these readings it will be seen that the values of the amplitudes of the self-oscillations and the telephone current increase together with increase of mutual inductance.

Further experiments made with cyclic grid potentials of frequency higher than 90 periods per second resulted in still louder signals as the low frequency more nearly approached the natural frequency of the telephones. But here considerable difficulty was encountered as it was found that once the cyclic grid potential had been increased to the value necessary for starting "trigger" action in the absence of an incoming signal, the voltage could be reduced considerably below the critical value before the trigger action stopped; and further, that within this region of hysteresis the receiver, once "trigged" by a signal, did not return to the quiescent state when the signal ceased. These phenomena, however, disappeared when the same receiver was used on smaller wave-lengths. It would therefore appear that, for satisfactory working, the ratio (radio frequency/low frequency) must not fall below a certain value determined by the constants of the circuit and the triode parameters. The authors found it possible to work satisfactorily between wave-lengths of 1 000 and 3 000 m with a range of low frequency from 250 to 90 periods per second, but further investigation of this point is to be desired.

As a matter of practical interest, and in view of the fact that the signals hitherto received had been exces-

Table 1.

Mutual inductance	Self-oscillation (galv. deflection)	Telephone current (galv. deflection)
mH.	div.	div.
0·284	0·6	2·0
0·44	4·0	5·0
0·604	12·1	7·0
0·79	17·0	14·5
0·97	22·0	18·0

sively loud, the system was tried with low values of anode voltage on the oscillator triode. With the anode connected to the positive end of the filament battery and the anode battery omitted, weak signals were received with the grid at about − 1·7 volts. With a further 2 volts on the anode the "backlash" region was about 0·3 volt, but it was found that in the middle of this region a small self-oscillation started, there being a further sudden increase of amplitude when the positive end of the region was reached. This necessitated the moving of the working point to the left of the centre of the backlash region, otherwise the signal was heard as a heterodyne whistle interrupted at the quenching frequency. In certain cases a state of absolute silence occurred at resonance, most probably due to the forcing of the feeble receiver oscillations by the incoming signal.* With the same connections and the anode at + 6 volts a nice loud signal was obtained and the effects enumerated above ceased to give trouble.

* Appleton: "The Automatic Synchronization of Triode Oscillators," *Proceedings of the Cambridge Philosophical Society*, 1922, vol. 21, p. 231.

Discussion before the Wireless Section, 21 November, 1923.

Mr. L. B. Turner: The paper is a valuable contribution to the understanding of the type of receiver employing an unstable retroactive triode circuit. The authors, having set up an oscillation circuit of this type, have calculated, in terms of the shape of the static characteristic for the triode [α, γ, ϵ, in Equation (5)], the possible amplitudes of oscillation. Their mathematics makes possible a calculation of the relations obtained experimentally in Fig. 3 (a), but the authors do not appear to have checked the theory against the observed curve HCGD. They then superpose a low-frequency fluctuation of grid potential, thus constructing an electrically quenched trigger relay. Again, the theoretical formulæ might be used to calculate the behaviour when the quenching rate is low. I think it was my own "Oscillatory Valve Relay," described and demonstrated before the Institution in 1919,* which first directed attention to the method underlying the subsequent developments of Bolitho, Armstrong, Flewelling, and the present authors. Indeed, in turning up a volume of my laboratory notes of the winter 1917–18, I find that I covered experimentally a great deal of that ground. But while the authors certainly must not be criticized for ignoring unpublished matter, I do think they have presented as new some facts which were already common knowledge. Thus in introducing the trigger principle on page 181 they say that "Some time ago [viz. 1922] Dr. van der Pol and one of the present authors found that, for a triode generator, there was often a pronounced difference between the limiting conditions for the starting and stopping of free oscillations." This fact is the very basis of my valve relay, and was stated and explained in the paper referred to, wherein, too, the now familiar terms "backlash" and "threshold" were coined. The authors also announce, in the summary and at the foot of page 183, the "remarkable fact" that oscillations, once started, can be maintained with a mean grid potential so low as to be well to the left of the static anode current characteristic. Readers of my paper could hardly be unaware of this; and the condition is, indeed, that ordinarily found in triode oscillators working at high efficiency. The trigger relay described by me was produced in response to a demand for a device to close a local circuit, not actuate a telephone. The relay which had therefore to be embodied was utilized to carry out the quenching of the oscillation by means of a switching operation; and for relay work I continued to prefer this switching quench after experimenting with many electrical methods of quenching, including that used by the authors. I was trying then to obtain a very rapid, preferably ultra-audible, quenching rate, in order to use the trigger device as a powerful auditive receiver as in the authors' arrangement, but competent to reproduce the pitch of the incoming signals. The various methods I tried ran through the alphabet (I see in my notes) from A to P, and I did not succeed in obtaining what I wanted. But I experienced in acute form the difficulties the authors also have felt (see page 186) in attempting to raise the quenching frequency. In Fig. 5, the oscillation in L_1C_1 does not leap instantly to its final value, nor die instantly to zero, when the critical condition for the maintenance of oscillations is passed through. Major A. C. Fuller measured delays amounting to nearly 0·02 sec. in one of my instruments working at a wavelength of 1 500 m. In attempting really rapid quenching I found at once that it was necessary actively to damp the oscillation during quenching—as Bolitho and Armstrong do—and not merely to remove the retroaction as the authors do. There is nothing to prevent the authors from quenching partly or wholly by a damping process. Even so, if the speed and/or wavelength are then sufficiently increased, it will be found that the response no longer rises, as in Fig. 6, very slowly with the signal strength, but is more or less proportional to the signal strength. The sudden threshold will have vanished, and by a slight further change the trigger relay will have been converted into the Armstrong amplifier. On the other hand, if the low quenching rates—such as the authors' 90 250 p.p.s.—are retained, the electrical quenching appears to me, from the point of view of practical convenience, to be less desirable than the switching quench that I preferred. I should be glad if the authors would state what is the minimum practical signal strength required in their experiments. I do not see that a closer margin should be feasible with electrical quenching than with the switching quench, and with that I used to consider that about 0·05 volt was required.

* *Journal I.E.E.*, 1919, Supp. to vol. 57, p. 50.

Mr. E. B. Moullin: The authors' elegant analysis of the action of trigger relays is very welcome, for it enables us to calculate the amplification that can be obtained. Thus, using the authors' notation, if a marginal value a_2 is exceeded an oscillatory potential a_3 is produced, and the amplification for any stated margin may be defined by the ratio a_3/a_2. For satisfactory working the margin must have a lower limit greater than zero: the value of this lower limit depends on the steadiness of the valve batteries and other local conditions and probably is fairly definite for a given type of triode. I hope the authors will continue their analysis so that the amplification can be calculated more readily. The symbol v in Equation (5) is the departure of the grid potential from its mean value, and α, β, γ, etc., are different for each different grid potential. The present analysis allows us to calculate how the ratio a_3/a_2 depends on the circuit constants R, C and M when the mean grid potential is fixed, but it does not allow us to calculate how that ratio depends on the mean grid potential, because α, β, γ, etc., are unknown functions of this quantity. We do not know, therefore, how to design the circuit to suit the valve. If the characteristic can be referred to a fixed origin (say, zero grid potential) instead of a wandering one it will be a great advantage. I think that it is possible to leave the equations as they are and perform the transformation in P and N only; if that is so the alteration should not be difficult to make. I should be glad if the authors would calculate the slope of the

curve HB in Fig. 4 at a point very near to B. I hope that the analysis will be extended to cover the case where the grid potential is subjected to a part only of the fluctuations of potential occurring across L. In Fig. 3 (*a*) it is seen that when the grid is at -20V the oscillatory current is more than twice as great as when the grid is at $+ 6$V, and we might gain from this the impression that the output as well as the efficiency of a generator is greatest when the grid is made very negative. The explanation of the apparent anomaly is that the circuit of Fig. 1 was an unsuitable one with which to obtain a large output. If by choosing L_1 suitably the authors find that while still retaining the hysteresis loops they can get a curve connecting oscillatory current and grid potential which has a positive instead of a negative slope, they will be able to show us how to use the relay to much better advantage than it was being used when the observations shown in Fig. 3 (*a*) were made. If we attempt to combine the functions of a chain of amplifiers and of a rectifier in a single relay, then it must be both a good amplifier and a good rectifier. I think that the authors' method of quenching the relay may compare unfavourably with the mechanical method used by Mr. L. B. Turner, because it lessens the rectifying capabilities of the triode. In the authors' method the net change of mean anode current is the resultant of two opposing effects, viz. an increase of mean anode current owing to the rectification produced by the curvature of the characteristic, and a decrease of normal anode current and of rectified current resulting from the progressive decrease of mean grid potential. Let us trace these changes as the portion BCH of the cycle shown in Fig. 3 (*a*) is traversed by the grid potential. When oscillations begin at the point B there is an anode current due to the mean grid potential OB, and a net increase due to the oscillation BC. As the grid potential proceeds from B to A the anode current due to the mean grid potential falls to zero, and the net increase due to the oscillation decreases because no anode current flows during a portion of the positive half-cycle of high-frequency P.D. Just before arriving at H the mean anode current may be sensibly zero and remain so until the oscillation is restarted at B. With mechanical quenching all the rectification occurs at the same mean grid potential. To obtain the best results from a trigger relay quenched by the authors' system I think that it may have to be combined with a separate rectifier valve, and in this case part of the advantage inherent to a trigger relay is lost. The authors' system may possibly be advantageous for minimizing atmospheric disturbances, because the relay is sensitive for a small portion only of the cycle of grid potential. An atmospheric would not actuate the relay unless it occurred when the mean grid potential was near OB, and the disturbance would be independent of the strength of the atmospheric, but this advantage is gained only by waste of transmitter power, for signals occurring when the grid potential is far from OB are inoperative. I think that the periodic time of the local E.M.F. must not be greater than the time of duration of a Morse dot, otherwise a dot may begin and end without having had an opportunity of actuating the relay. An increase in the speed of signalling will, however, call for a more than proportionate increase in the frequency of the local E.M.F., because the signal may not have time to build up the marginal P.D. if given only one opportunity. But, as the authors point out, the ratio of radio frequency to local frequency must not fall below a certain amount or quenching ceases, presumably because the free oscillation left in the circuit after the point H has been passed must be given time to die down to a residuum which is less than the marginal value required for restarting. The critical ratio would be decreased by increasing R or decreasing L_1, the sensitivity being maintained by adding to the anode battery. Do the authors consider that if, when distuning their receiver, they had maintained the operating P.D. constant in value and frequency instead of keeping the transmitter current constant, they would still have obtained results similar to those illustrated in Fig. 7? Do they imply that an E.M.F. competent to actuate the relay must have not only a certain marginal value but also a frequency nearly the same as that of the receiver circuit? Does their analysis suggest that the receiver could not be actuated by moving it at a uniform speed across a constant magnetic field?

Mr. T. L. Eckersley: The chief value of the paper lies, in my opinion, not so much in its novelty (for

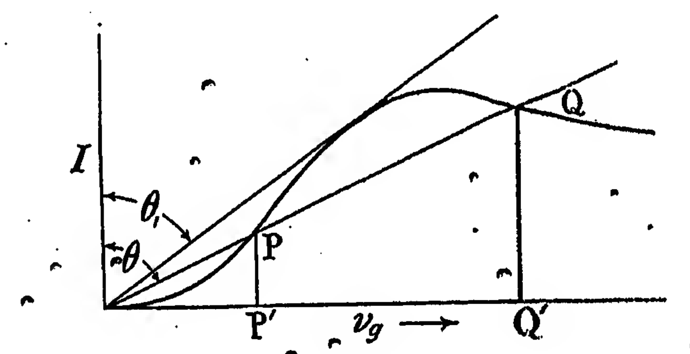


FIG. A.

Mr. Turner has previously used a very similar device) as in its clear mathematical exposition. The authors use a method in which they express the valve characteristics as a series of powers of what we might call the characteristic voltage V, i.e. $(V_A + mV_g)$, where V_A is the anode voltage, V_g the grid voltage, and m the magnification constant of the valve. There is another method in which the anode-current/grid-voltage characteristic can be expressed as a Fourier function of the characteristic voltage. Two or three years ago I attacked the problem of what the authors call "oscillation hysteresis" from this point of view. A tuned anode circuit was assumed in which the harmonics are supposed to be small compared with the fundamental, so that a practically sinusoidal voltage is impressed on the grid. Under these conditions we plot the actual oscillatory current in the plate circuit against the grid voltage, and get a curve of the form shown in Fig. A, which may be calculated from the characteristic as follows: If we express the characteristic curve as

$$i_p = A_0 + A_1 \sin(2\pi\beta) + \ldots + A_n \sin(2n\pi\beta) \ldots \text{etc.}$$
$$B_1 \cos(2\pi\beta) + \ldots + B_n \cos(2n\pi\beta)$$

V = characteristic voltage, where $\beta = V/V_0$, V_0 being some fixed arbitrary value of V.

Then $$I = \frac{Lp}{R} f(\beta_1)$$

where $\beta_1 = \frac{V_g}{V_{g0}}$; and $V_{g0} = \left(1 - \frac{L}{M_m}\right) V_0$;

L = inductance of oscillatory circuit;
M = mutual inductance to grid circuit; and

$$f(\beta_1) = (A_1 + B_1) J_1 (2\pi\beta_1) + (A_2 + B_2) J_1(2\pi 2\beta_1) + \ldots + (A_n + B_n) J_1 (2n\pi\beta_1)$$

where J_1 is a bessel function of order 1.

The conditions for the production of oscillations may be shown as follows: If we draw a line at an angle θ with the vertical axis, where $\tan\theta = M_p$, then the condition that self oscillations may be produced is that the line OPQ shall cut the (V_g, I) curve. In the figure the lines cross at O, P and Q, showing that three modes of oscillation are possible. These correspond to the three roots of the equation obtained by Dr. Appleton: one is of zero amplitude and is stable; the next, PP′, is unstable; and the other, QQ′, is stable again. The figure shows that with a given value of the reaction, determined by the angle θ, no oscillations can be maintained until an initial grid amplitude greater than OP′ is produced. This is the threshold value of grid voltage; once this voltage is produced the plate current automatically builds up to the value QQ′. These oscillations can be stopped by reducing the reaction M to the value $\tan\theta_1/p$, where the line θ_1 is tangential to the V_g, I curve. The method given here is more suitable for expressing the dependence of the oscillations on reaction rather than on the initial grid voltage, but it is possible by drawing the representative curves for various initial grid voltages to determine the effect of varying grid bias as well, but not so clearly. Obviously a large negative bias on the grid shifts the whole (V_g, I) curve to the right, and a bigger threshold value of V_g is necessary to start the oscillations, just as described in the paper. This method can be used to take account of the harmonics, but naturally becomes increasingly complex when more of these are included. The practical utility of the device which avowedly depends for its action on the non-linear characteristics of the triode, is, in my opinion, marred for this reason. The majority of wireless engineers try to avoid as much as possible anything which savours of "non-linearity." The reason for this is that the problem of interference is generally made more difficult by the introduction of non-linear characteristics, for the cross terms, due to the interaction of the signal and the disturbance, make impossible any method for the separation of the two. The fact that the characteristic note of the signal is lost, making telephony impossible by this method, is also traceable to the non-linear relation, which is therefore to be treated with great care.

Mr. R. C. Clinker: I am reminded of an experiment that I carried out some years ago with a single-valve receiver. I am not quite sure whether the effect was the same as described in the paper, but it was actually this. I was using a coil aerial, about 12 in. × 10 in. with about 200 turns on it, and a single valve with the anode circuit reacting direct on to the coil, for receiving Nauen, that is, the spark station. If I increased the coupling of the circuit so as to cause the valve to howl, that is, to make a certain unmusical note, I could easily read the signals from Nauen anywhere in the room with this single valve and small coil, because the signal changed the pitch of the howl just enough to enable the Morse to be read. I am not quite clear what the action was, but I imagine it was something like that described in the circuit shown in the paper, except, of course, that the howl was acting as the low frequency. It was simply a change in pitch—a very slight one—when the dots and dashes came in from Nauen, but it enabled the signals to be read anywhere in the room.

Major H. P. T. Lefroy: In reply to the authors, who ask for the experience of those who have used this method of reception, my results obtained in March 1922, when experimenting on high-frequency line telegraphy, may be of interest. I used a "trigger" arrangement which gave excellent results for high-speed work. I was transmitting, with the permission of the G.P.O., from Fenny Stratford on a subterranean cable, and receiving in London, the distance being 52 miles. The high-frequency energy input was rather less than 1 watt, and the received E.M.F. was about 1/1 000th of the input E.M.F., owing to attenuation along the cable. I received at the rate of 200 and 240 words per minute quite comfortably, on frequencies of 10 000 and 6 000 p.p.s. respectively. In the arrangement which I used, the incoming signals "triggered" a three-valve amplifier, controlled so as to be on the verge of self-oscillating when awaiting signals. Using a standard G.P.O. relay, I got, with strong incoming signals, a change from zero current in the relay circuit to 50 mA, and this enabled me to record 240 words per minute on tape. Using a specially wound relay of 8 000 ohms resistance, I got zero to 16 mA, which was still better for high-speed work. I then attempted reception at high speed on a subterranean cable on which the Post Office, about a mile distant, were working on Wheatstone automatic at 80 words per minute from London to Carlisle, this producing on my receiver the equivalent of severe atmospherics. After a little experimenting I was able to cut this disturbance out and receive at 100 words per minute from Fenny Stratford. I was struck with the freedom from jamming in this "trigger" method of reception, in view of the extraordinary strength of the Wheatstone interference, and I assumed then that this was due partly to the filtering arrangement that I was using, and partly to the fact that the only time when jamming could be effective was when the disturbance arrived during a spacing interval.

Major A. G. Lee: The authors lay stress upon the effects of the non-linear conductance of triodes in modern wireless circuits, and I should like to call attention to what I think is an equally fundamental principle governing the operation of some of those circuits. This, briefly, is that if we have a subsidiary E.M.F. acting in a resonant circuit, this E.M.F. may be regarded as contributing an impedance to the circuit. This impedance, depending upon the phase of the subsidiary E.M.F. in relation to the current in the circuit, may consist of either positive or negative resistance in

combination with positive or negative reactance. When dealing with forced oscillations this view-point gives exactly the same result as that arrived at by the normal process of adding the main E.M.F. and the subsidiary E.M.F. vectorially, and there is no advantage gained by looking at the process from this angle. With free oscillations, on the other hand, the phenomenon of the frequency being changed by the presence of the subsidiary E.M.F. is more readily understood when looked at from this point of view. For instance, in the normal operation of coupled circuits the effect of the reaction from one circuit to the other is to separate the frequencies of the self-oscillations. I have, however, found it possible to synchronize two damped, free oscillations of widely different natural frequencies by arranging suitable initial amplitudes and phases in the two circuits, and this was done without the intervention of a triode with its non-linear conductance. In the ordinary transformer case the current in the secondary is a function of the current in the primary, and its reaction on the primary is usually such as to change the natural frequency of that circuit. This is a particular case of the more general one outlined above in which it is indicated that the current in the second circuit can be a completely independent one and the effect of the current in the second circuit on the first may be regarded as the insertion of an impedance in the first circuit. Dr. Appleton's investigation into the "synchronization of triode oscillators" appears to me to be an example of this type of action. The theory is competent to explain the synchronization when the phase has arrived at the correct relation, though the quantitative explanation requires a knowledge of the triode currents, i.e. the non-linear conductance theory. It would also explain the pulling together of the frequencies outside the range of synchronization, which is another very important point to which Dr. Appleton has called attention, but it is to be expected in this case that there would be a cyclical change in the frequencies. Another interesting case is that of the ordinary triode oscillator such as that in Fig. 1 of the paper. In this case the effect of an oscillating current in the grid resonant circuit is to induce a current in the anode circuit through the coupling M_1, which, reacting back on the grid circuit by ordinary transformer action, increases R and decreases L of the circuit. The effect of the component of current in the anode circuit which is controlled by the grid potential is, however, to decrease R and increase L. As the latter effect is greater than the transformer effect, in general this type of oscillator oscillates at a lower frequency than that given by the L and C values of the circuit. There is a certain family of phenomena which are rather grouped together in my mind as being dependent upon this type of action, viz. the triode synchronization phenomena described by Dr. Appleton; the "Ziehen" effect investigated by German writers; the discontinuities in phase and frequency in coupled circuits in valve and arc transmission; the separation of frequencies in damped oscillations of coupled circuits; and various effects met with in ordinary triode retroacted circuits (not self-oscillating), such as the mistuning effect of retroaction when its phase is changed, etc. Some few years ago trigger systems of reception were somewhat popular, but their popularity quickly died. My own experience with them was disappointing. I found that their principal drawback was that they would not receive weak signals; and, after all, it is the weak signal which is the principal difficulty in wireless reception. It is quite easy to receive a strong signal by any other method. Some trigger systems, e.g. the Bolitho system, show a certain amount of advantage in reducing atmospheric interference, as the atmospheric is cut short by the quenching action.

Lieut. G. W. N. Cobbold: It seems to me of little value to consider, as Mr. Moullin has done, the ratio of a_3 to a_2, for the operation of this system, in which the character of the incoming signals is lost, involves essentially relay action rather than amplification. The device must accordingly be compared with a trigger system employing a mechanical relay; and in such a system the ratio of output to input may be increased indefinitely. I should therefore be glad if the authors could give us further information concerning the magnitude of the minimum signal required to operate their device, for one of the most important criteria by means of which it is customary to judge a trigger system is the value of the "backlash," i.e. the difference between the grid voltage at which the triode just bursts into violent oscillation, and the grid voltage at which the oscillations are killed. It was my privilege to assist Major Fuller at the Signals Experimental Establishment during some of the early developments of the Turner trigger relay for high-speed reception, and I have seen a good deal of the more recent improvements effected by Dr. Brydon. As a result of these developments at the Signals Experimental Establishment a very high standard of excellence has been reached; and, whilst wishing to thank the authors for their interesting mathematical analysis, I venture to doubt whether they have even approached in their practical apparatus the excellence of the instrument that was demonstrated before the Institution after the reading of Col. Cusins's paper on the 4th January, 1922.

Dr. E. V. Appleton and **Mr. F. S. Thompson** (*in reply*): We do not wish the method of reception which we have described to be regarded as being put forward by us as a rival to the Turner trigger relay system or to the methods of similar type described by Bolitho, Armstrong or Flewelling. In describing the periodic trigger method our chief aim has been to exhibit as transparently as possible the theoretical basis on which the method rests, since we have not as yet had time to examine all the practical aspects of it in detail. Since the paper was read we have been able to compute the oscillatory signal necessary for successful working with periodic trigger reception. As was stated in the paper, satisfactory signals were obtained on the coil of the receiver from GLA (Ongar), which station is about 30 miles from Cambridge. Through the courtesy of Mr. T. L. Eckersley of the Marconi Company, who has kindly supplied the necessary data, we have been able to calculate the field strength at Cambridge and thus estimate the oscillatory electromotive force impressed on the receiver coil. This computed electromotive force is found to be 5×10^{-5} volts. The actual value is, of

course, likely to be much less than this as no absorption has been allowed for.

In reply to Mr. Moullin's point regarding inefficient rectification, we can only say that for all practical purposes we have found the rectification sufficient, since when the receiver is "trigged" in any way the signal in the telephones is deafening. We also intended it to be understood that a signal of sufficient magnitude within a fairly wide range of frequencies would operate the receiver in the same way.

The graphical method of calculating the amplitude of a triode generator described by Mr. Eckersley is very similar to that described by one of the authors in the *Radio Review*, 1921, vol. 2, p. 424.

The phenomenon described by Mr. Clinker is, we think, quite different from that underlying periodic trigger reception. We have ourselves observed the same phenomenon as Mr. Clinker, using a condenser and grid leak in the receiver. In such a case with strong coupling the circuit may be made to oscillate in periodic trains, giving rise to an audible note in the telephone. A received signal, however, alters the mean grid potential slightly and the frequency of these periodic trains is altered—due to the alteration in the time of the discharge of the grid condenser. The telephone note is thus altered by the signal.

Major Lee's remarks on the problem of the synchronization of triode oscillators are particularly interesting to us, for it was by this linear treatment (which, as Major Lee admits, is necessarily incomplete in the case of triode circuits) that the problem of synchronization phenomena was first attacked before the more complete non-linear theory was worked out. As a result of this preliminary work it was found that for practical purposes it could be assumed that a circuit of natural frequency ω_0 is changed slightly to one of frequency ω by a periodic impressed E.M.F. such that

$$\omega_0 - \omega = \frac{E_0\omega}{2a}\cos\phi$$

where E_0 is the impressed E.M.F., ϕ is the phase difference between the impressed E.M.F. and the vibration, and a is the amplitude of the vibration. No doubt this formula would explain the phenomena mentioned by Major Lee. In the case where actual synchronization does not occur the same formula is approximately true, and we note that the free frequency varies with ϕ during a beat, giving rise to beats of an anomalous type previously described. A treatment of synchronization phenomena, which is more satisfactory mathematically than that previously mentioned, has recently been worked out. This deals with the attraction of frequencies observed experimentally. It is hoped that it will be published shortly.

Major Lee's experiments on the synchronization of damped linear vibrators are of very great theoretical importance and we hope that an account of them will soon be published.

THE RELATIONS BETWEEN DAMPING AND SPEED IN WIRELESS RECEPTION.

By L. B. TURNER, M.A., Member.

(*Paper first received 12th June, and in final form 9th November; read before the* WIRELESS SECTION *5th December*, 1923.)

SUMMARY.

Part I is devoted to an examination of the ordinary method of recorder working in wireless telegraph receivers, as affected by the damping of the receiver circuits. After a résumé of the significances of the decrement of any oscillatory system, its bearing on the possible speed of recording Morse signals is investigated. The quality (approach to correct Morse "shaping") is estimated from calculated curves of amplitude of oscillation set up in the receiver by the incoming dots and dashes constituting the letter "l." By comparing several such curves, a minimum practical value is found for the product of frequency and decrement and duration of Morse dot. The relation between speed of signalling and the requisite transmitter power is then investigated. Part I concludes (Section 5) with a summary and discussion of the results arrived at.

In Part II an improved method of reception, called "receiver curbing," is described and analysed. An estimate is made of the improvement obtainable, and practical circuits are given for putting the method into effect.

Part I.—ORDINARY RECEPTION.

(1) *Introduction.*—Ever since Lodge's enunciation of the importance of syntonization in wireless telegraphy—embodied in his famous patent 11575 of 1897—efforts have been made to produce electrical oscillatory systems, both transmitting and receiving, of low damping. Owing to the regrettable fact that we happen to have no materials for electrical conductors exhibiting much less resistance than do copper and silver, low damping was much more difficult to obtain in electrical than in mechanical systems (e.g. in the pendulum of an astronomical clock); but in recent years the thermionic triode has conferred upon us, amongst its other boons, the power of contriving negative resistance, thus enabling us to construct with ease electrical oscillatory circuits of extremely low damping. This advance in our technical abilities, combined with the general transition towards the use of longer waves and higher signalling speeds, has now greatly modified the situation, so that at the present time cases readily arise in which we have, so far from striving for the lowest attainable damping, to inquire rather how far it is in our interest to go.

In this paper one aspect is examined of the relation of damping to the reception of wireless signals, viz. its relation to the "shaping" of the received dots and dashes, using "shaping" in the sense in which it is used in cable telegraphy. It is surprising that the subject has not (as far as I am aware) attracted attention already, for its study is essential to an understanding of the relations existing between speed of working and transmitter power. The time has come when the problem of recorder speed in wireless calls for something of the effort which has been expended, with such beneficent results, on the like problem in submarine cable telegraphy; and it is hoped that this paper may help in preparing the way for the copious high-speed long-distance wireless traffic of to-morrow.

Let us first briefly review the significance of damping in oscillatory systems, and the terms in which it is measured. The disturbance in any oscillatory system where a quantity q varying with time t is described by the differential equation

$$L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{1}{C}q = 0$$

dies down according to its solution

$$q = q_0\,\epsilon^{-mt}\cos pt \quad \text{(see Fig. 1)}$$

where $$m = \frac{R}{2L}$$

and $$p = 2\pi n = \sqrt{(CL - m^2)}$$

$$\approx (\sqrt{CL}) \text{ when } \frac{m^2}{p^2} \ll 1$$

The amplitude dies down according to the damping factor ϵ^{-mt} or $\epsilon^{-(m/n)N}$, where N is the number of periods

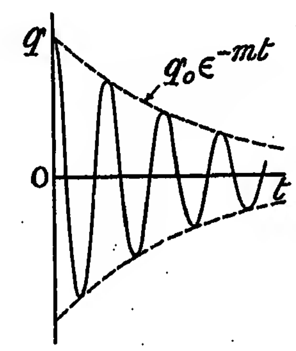


FIG. 1.

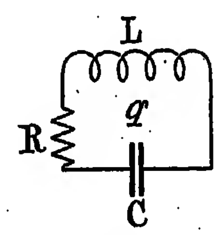


FIG. 2.

of the oscillation; the rate of fall is specified with reference to the number of seconds of time by the decay coefficient m, or with reference to the number of periods by the ratio $\epsilon^{m/n}$ of the successive maxima. The logarithm of this ratio, m/n, is called the logarithmic decrement—or briefly the decrement—δ of the oscillatory system, and we may write

$$q = q_0\epsilon^{-\delta N}\cos pt$$

The decrement $\delta = m/n = R/(2nL)$ specifies the period rate at which the oscillation dies away; thus the amplitude is divided by $\epsilon = 2\cdot 7$ during every increment of $1/\delta$ in the number of periods, N.

When the oscillatory system is an electric circuit as in Fig. 2, q is the quantity of electricity displaced, and the dimensions L, R and $1/C$ of the system are the inductance, resistance and reciprocal capacitance respectively of the circuit.

The root significance of the decrement is that just stated. But there are other properties of the circuit equally well specified by its decrement. When the circuit is excited by an impressed alternating E.M.F., say $e = E \sin p_1 t$, its final response depends upon the "tuning" (i.e. relation between p and p_1) in a degree determined by the decrement. The selective property of the circuit as regards frequency of impressed E.M.F. is well exhibited by the familiar "resonance curve" connecting final amplitude with the impressed periodicity, p_1. The lower the decrement the "sharper" this curve and the "sharper" the tuning; thus, in Fig. 3, $AB/OC = \delta/\pi$.

A third, quite different, significance of the decrement of the circuit is this: it specifies the period rate of growth of the oscillation engendered by the impressed E.M.F. when of the resonant frequency. Thus

$$L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{1}{C}q = E \sin p_1 t$$

$$q = q_0\epsilon^{-mt}\cos(pt + \theta) - q_1 \cos(p_1 t + \phi)$$

where $$q_1 = \frac{E}{p_1\sqrt{[(1/p_1C) - p_1L]^2 + R^2}}$$

and $$\tan\phi = \frac{1/(p_1C) - p_1L}{R}$$

and q_0 and θ depend upon initial conditions. In the particular case of resonance ($p_1^2 = 1/CL$), low damping ($m^2/p^2 \ll 1$), and the circuit quiescent and discharged when the E.M.F. was first applied ($q = 0 = dq/dt$, when $t = 0$), this becomes

$$q = -\frac{E}{pR}(1 - \epsilon^{-mt})\cos pt$$

$$i = \frac{dq}{dt} \approx \frac{E}{R}(1 - \epsilon^{-mt})\sin pt$$

$$= \frac{E}{2L} \times \frac{1 - \epsilon^{-mt}}{m}\sin pt$$

$$= \frac{E}{2nL} \times \frac{1 - \epsilon^{-\delta N}}{\delta} \times \sin pt$$

The factor $(1 - \epsilon^{-\delta N})/\delta$ is plotted against N for several values of δ in Fig. 4. These curves show that after the lapse of (say) 500 periods from switching on the E.M.F., if $\delta = 0{\cdot}01$ the full amplitude has sensibly been reached; if $\delta = 0{\cdot}001$ the amplitude is still rapidly rising, having reached only about 40 per cent of its final value; and if $\delta = 0{\cdot}0001$ the amplitude is only 5 per cent of its final value. Let us now suppose that the E.M.F., $E \sin pt$, switched into our oscillatory circuit constitutes an incoming wireless signal which, when making a Morse dot, lasts for (say) 500 periods, and, when making a dash, for 1 500 periods. If $\delta = 0{\cdot}01$ the amplitude reached during dot and dash are sensibly equal and of magnitude $100 \times E/(2nL)$; if $\delta = 0{\cdot}001$ the dash amplitude is nearly twice the dot amplitude, which is $400 \times E/(2nL)$; and if $\delta = 0{\cdot}0001$ the dash amplitude is nearly three times the dot amplitude, which is about $500 \times L/(2nL)$.

An actual receiving circuit must respond to both dots and dashes, separated moreover by only a dot-length of spacing interval. It is obvious, therefore, that if conditions resembling those of the last two cases should prevail, the indicator, whether telephone or relay and recorder, would be asked to perform an impossible task; it could not reproduce anything like an accurate copy of the Morse signals transmitted. The difficulty with respect to the receiving instruments is precisely that met in the reception of submarine cable signals, although originating in the terminal apparatus instead of the medium connecting them.

The curves of Fig. 4 show not only the relative importance of the transient stages in the building up of the oscillation (in that respect obviously $\delta = 0{\cdot}01$ is much

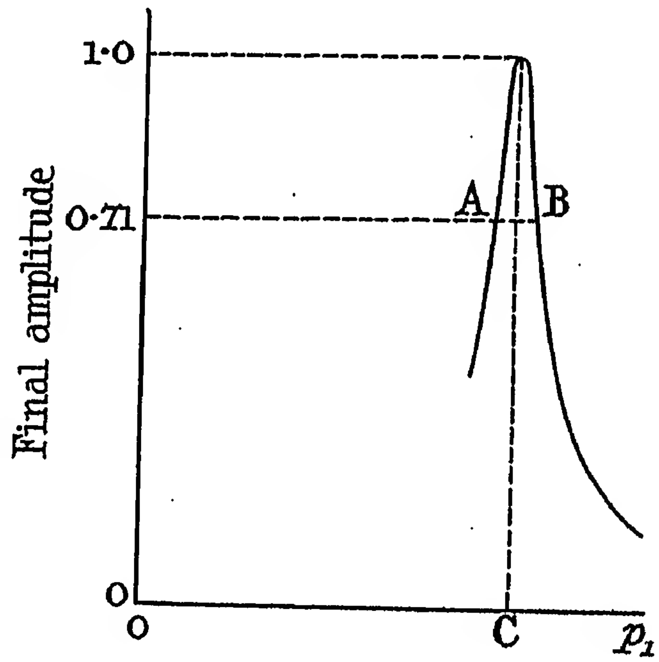


FIG. 3.

more desirable than $\delta = 0{\cdot}001$) but they show also the relative sensitivities of the receiver (assuming that the change of decrement is due to change of resistance). In this respect the sensitivity of $\delta = 0{\cdot}001$ is 10 times that of $\delta = 0{\cdot}01$ for indefinitely slow signals, and is 4 times for dots lasting 500 periods. It is, moreover, easy to see that gain in respect of selectivity between one frequency and another accompanies the gain in sensitivity; so that in these respects $\delta = 0{\cdot}001$ is much more desirable than $\delta = 0{\cdot}01$.

Now it is practicable to build receiving circuits whose decrement, due to inherent resistance, is as low as $0{\cdot}01$ or less, and by familiar retroactive triode arrangements the decrement can be reduced with adequate stability far below this figure, certainly below $0{\cdot}001$. It is therefore within our powers to provide very low decrements, and we have a task of practical interest in seeking for an optimum compromise amongst the above-mentioned conflicting claims in favour of high and low decrements. To utilize very low decrements it is, of course, necessary to provide very close resonance; and at present it is probably often the case in practice that the precision of tuning is quite inadequate,

e.g. owing to inconstancy of transmitter frequency. This is, however, an unnecessary imperfection, and with the modern type of thermionic transmitter in which a feeble unbroken master oscillator energizes the aerial through a key-controlled chain of amplifiers, it may be assumed that sensibly perfect syntony is obtainable.

(2) *Some calculated arrival curves.*—We begin our investigation by calculating the arrival curves—to borrow an appropriate cable term—for a representative sequence of Morse dots and dashes, viz. the letter "1" (· — · ·). Including the letter space ($3T$) following at the end, this signal in the Morse code has a total duration $12T$, where T is the duration of a dot and $3T$ the duration of a dash. We will suppose that the E.M.F. impressed in our oscillatory circuit is sensibly

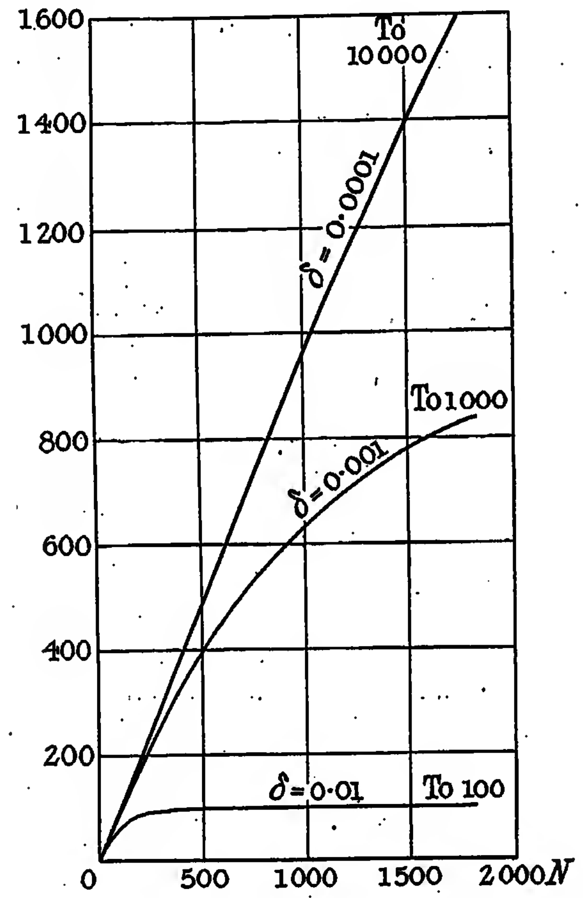


FIG. 4.

"square-shaped," i.e. rising suddenly from 0 to $E \sin pt$ at the beginning of a mark and falling suddenly to 0 at the end.

During a signal, the amplitude A of the oscillatory current in the receiving circuit is

$$A = \frac{E}{2nL} \times \frac{1 - \epsilon^{-n\delta t}}{\delta}$$

Its value $\dot{A}$* at the end of a dot lasting T secs. is

$$= \dot{A}\ \frac{E}{2nL} \times \frac{1 - \epsilon^{-n\delta T}}{\delta}$$

Its value $\bar{A}$ at the end of a dash is

$$\bar{A} = \frac{E}{2nL} \times \frac{1 - \epsilon^{-3n\delta T}}{\delta}$$

* Note that $\dot{A}$ does not mean $\frac{d}{dt}(A)$.

During a space it falls from its value at the end of the preceding mark according to the damping factor $\epsilon^{-n\delta t}$. Hence at the end of a short space following a single dot its value is

$$\dot{A}_s = \dot{A}\epsilon^{-n\delta t}$$

$$= \frac{E}{2nL} \times \frac{\epsilon^{-n\delta T} - \epsilon^{-2n\delta T}}{\delta}$$

and following a single dash it is

$$\bar{A}_s = \bar{A}\epsilon^{-n\delta T}$$

$$= \frac{E}{2nL} \times \frac{\epsilon^{-n\delta T} - \epsilon^{-4n\delta T}}{\delta}$$

The curves of amplitude of "received current" given by these formulæ are plotted, on a time base with T as the unit, for a single dot and space (dotted line) and a single dash and space (full line) in Fig. 5, in the case where $n\delta T = 2$.*

When the E.M.F. reappears at the end of a space the amplitude has not fallen to zero; hence the behaviour at the beginning of the next mark must depend on the phase relation between the residual oscillation and the new impressed E.M.F. If perfect synchronism between transmitter and receiver still obtains at the end of the space, the dying residuum is added to the growing new oscillation; but if they have got into anti-phase, the

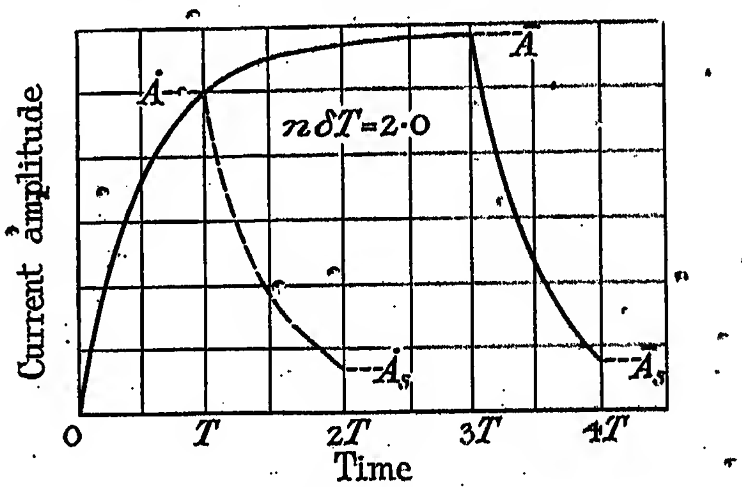


FIG. 5.

new E.M.F. (and the lapse of time) must reduce the residuum to zero before building up the new oscillation. With a keyed oscillator at the transmitter this phase relation is probably usually a matter of chance; but with the master-oscillator type of transmitter referred to at the end of the last section, already in fairly common use, the new E.M.F. may be assumed to be in phase with the residual oscillation, i.e. no phase displacement is introduced during the spacing epoch. For the arrival curves calculated in Fig. 6 and subsequent diagrams, an exact in-phase relation is assumed, but at the beginning of the last dot the effect of the anti-phase relation is also portrayed (in chain-dotted line), so that the significance of the phase relation may be seen in the several examples shown.

To ascertain the response of a relay actuated by this

* To make these curves more concrete, they may be applied to any interesting numerical case satisfying the specified condition $n\delta T = 2$, for example:— $\lambda = 10\,000$ m; $n = 30\,000$ p.p.s.; $\delta = 0{\cdot}0067$; $T = 0{\cdot}010$ sec. (i.e. signalling speed 125 words/min.).

received oscillatory current; we must know the operative amplitude A_0 above which the relay marks and below which it spaces.* If we were concerned only to operate the relay—without regard to the shaping of the signals recorded—the ratio between A_0 and the greatest amplitude attained would be made as near unity as practicable, in order to favour as much as possible the tuned signal E.M.F. in the contest with distuned E.M.F.'s, particularly atmospherics. In this connection it is important to distinguish between the sensitiveness of the relay *per se*, and the sensitiveness of the receiving circuit as a whole. The former is irrelevant, because the relay does not select between desired signals and "jamming"; the latter is very important, for while the tuned signal E.M.F. is competent to make the amplitude climb to the operative value A_0, an equally strong E.M.F. of other frequency is not competent. If our friend is provided with a good ladder and our enemies have poor ladders, it is well to build our wall nearly to the height of our friend's ladder.

The choice of A_0 is, however, dependent on questions of shaping. Referring to Fig. 6, if the relay is biased or otherwise adjusted to make A_0 too high, it will register dots too short, and there is danger of missing them altogether in the event of a slight departure from the ideal conditions. Again, if A_0 is too low, the relay will register the spaces too short and there is danger of running successive marks together. The best compromise can only be found by trial, and must depend to some extent on the quality of the recording apparatus. In Fig. 6, fairly accurate Morse shaping would be given by $A_0 = 0 \cdot 60$, but since easy legibility of the record depends much more on uniformity as between dot and dot, space and space, etc., than on the closeness of reproduction of their relative lengths in the Morse code, it is thought that $A_0 = 0 \cdot 70$ would be a preferable value.* The signals which would be recorded with $A_0 = 0 \cdot 70$ are shown in Fig. 6 by the thick lines drawn across the arrival curves at that height, and for comparison with them the true Morse-shaped transmitted signals are shown just above.

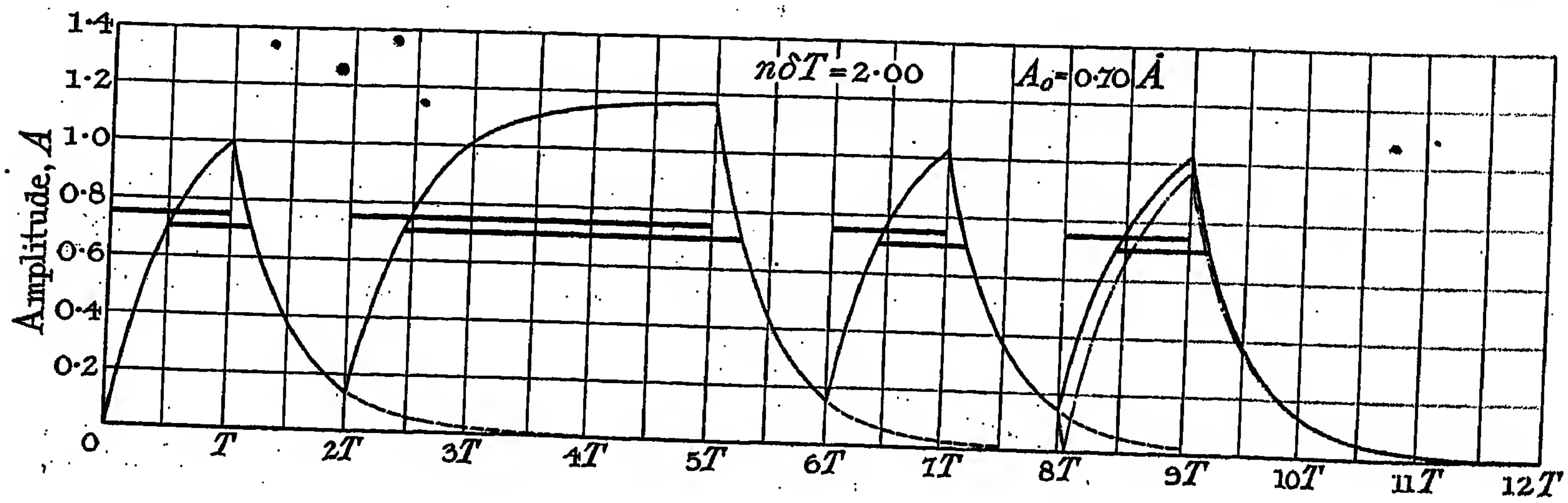


FIG. 6.

In Fig. 7 the corresponding curves are drawn for $n\delta T = 1 \cdot 50$, and in Fig. 8 for $n\delta T = 1 \cdot 00$. In Fig. 7 it is seen that good uniformity cannot be obtained with any value of A_0, but fairly good signals are obtained with $A_0 = 0 \cdot 75$ as a compromise between seriously unequal first and second dots if $A_0 > 0 \cdot 75$, and seriously unequal first and second spaces if $A_0 < 0 \cdot 75$. The signals for $A_0 = 0 \cdot 75$ are shown on the curves. In Fig. 8 no approach to uniformity can be obtained, whatever value is given to A_0.

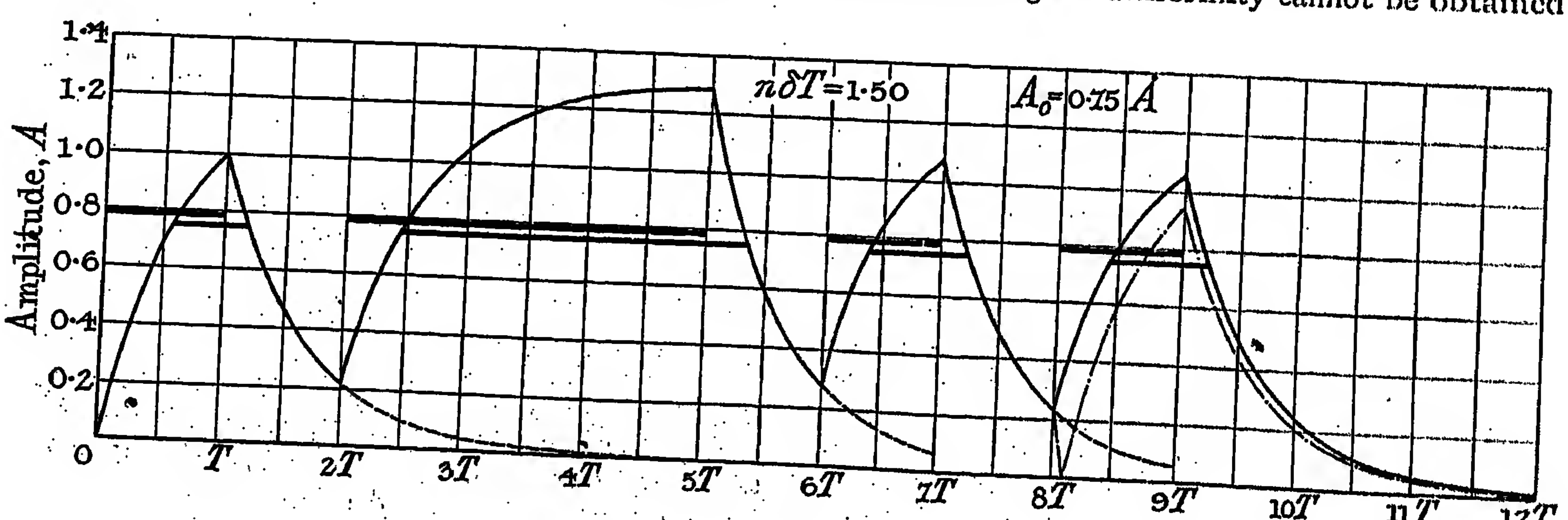


FIG. 7.

(3) *Minimum permissible value of $n\delta T$.*—It has been

* For simplicity we take no account of the necessary, though maybe very small, difference in the critical currents when rising to mark and falling to space, due to friction, etc., in the relay.

* Moreover, given uniformity, the clipped dots could always be restored by manipulation, mechanical and electrical, of the recording apparatus.

seen that the shape of the arrival curves is a function of $n\delta T$ alone, so that information as to shape gained

TABLE 1.

Wave-length	Words per minute	Decrement for $n\delta T = 2$	Decrements for lower sensitivities, S	
			$S = 0{\cdot}75\,S_0$	$S = 0{\cdot}50\,S_0$
m 1 000	200	0·0011	0·0016	0·0025
5 000	100	0·0027	0·0039	0·0062
	20	0·00054	0·00078	0·0012
20 000	100	0·011	0·016	0·025
	20	0·0022	0·0032	0·051

from a few trial curves such as Figs. 6, 7 and 8 is general for all wave-lengths, decrements and speeds of signalling.

low speeds of signalling), as has been seen already with reference to Fig. 4. It is therefore necessary to ascertain the relation between the decrement and the magnitude of signal E.M.F. requisite to operate the relay.

From Section (2) we have

$$A_0 = a\dot{A} = \frac{aE}{2nL} \times \frac{1 - \epsilon^{-n\delta T}}{\delta}$$

Therefore $$\frac{2nLA_0}{E} = a \times \frac{1 - \epsilon^{-n\delta T}}{\delta}$$

i.e. $$S = a\,\frac{1 - \epsilon^{-n\delta T}}{\delta}$$

where S (being proportional to A_0/E) measures the sensitivity of the receiver, when its decrement is δ, to tuned signals of wave-length given by n and speed by T. On account of the shaping of the signals we have

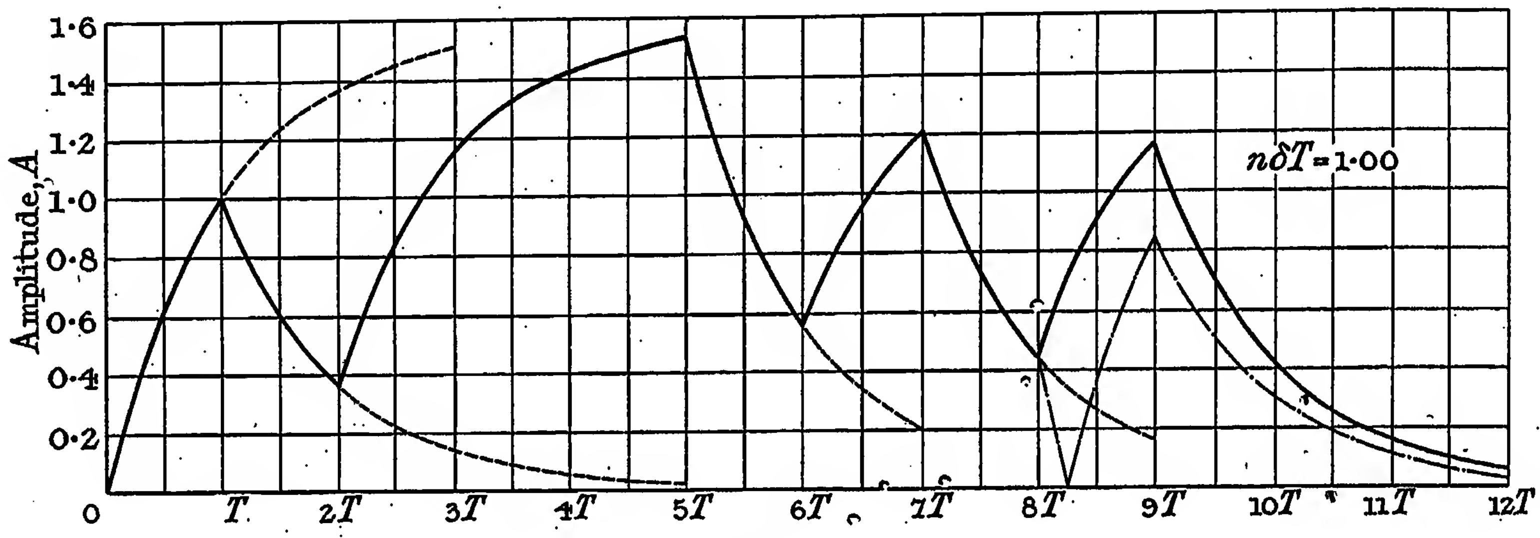


FIG. 8.

Where precisely to draw the line must be somewhat a matter of personal judgment. It is quite clear, however, that $n\delta T = 1{\cdot}0$ is too low, that $n\delta T = 1{\cdot}5$ is far from perfect, and that $n\delta T = 2{\cdot}0$ would give very readable signals. For the purpose of this paper, 2 is taken as the minimum permissible value of $n\delta T$ for any wireless recording, and this is done without reference to sensitiveness. On this basis, however strong the transmitter, $n\delta T$ must not be less than 2 if good signals are to be recorded. A few selected sets of values of wave-length, speed and decrement for which $n\delta T = 2$, are given in the first three columns of Table 1.

(4) *Power and speed of signalling.*—Table 1 illustrates how, for any specified wave-length and speed, we are limited in reducing the decrement of the receiving circuit by consideration of the shaping of the recorded signals. That as low a decrement as the shaping will allow is desirable, despite the modern facilities for almost unlimited amplification, is obvious when we reflect that the amplitude produced by an atmospheric or a distuned interfering signal is almost independent of the decrement, whereas the amplitude from the tuned signal E.M.F. increases as the decrement is reduced. The signal effect, however, is not linearly proportional to the reciprocal of the decrement (except at indefinitely

found that $n\delta T$ must not be less than 2, so that the optimum sensitivity is

$$S_0 = a\,\frac{1 - \epsilon^{-2}}{2/(nT)} = 0{\cdot}43\;anT$$

Therefore $$\frac{S}{S_0} = \frac{1 - \epsilon^{-n\delta T}}{0{\cdot}43\,n\delta T}$$

This ratio S/S_0 (viz. ratio between actual sensitiveness of receiver and sensitiveness when the decrement is reduced to its minimum permissible value at that wave-length and speed), is plotted as a function of $n\delta T$ in Fig. 9. At any given wave-length and speed, a decrement lower than $2/(nT)$ gives bad shaping, while any higher decrement reduces the sensitiveness to a fraction shown by the curve.

With the aid of Fig. 9, we can extend Table 1 to show, in the several numerical examples taken, the higher values of the decrements which reduce the sensitivities S from the optimum S_0 to (say) ·75 per cent and 50 per cent of S_0. This is done in the last two columns of Table 1.

To attach correct importance to the fall in S as the decrement is raised, it must be remembered that the

power required at the transmitter is proportional to the square of $1/S$. The minimum power, P_0, which at any given wave-length is competent to give a certain speed of working, is therefore proportional to the square of that speed, for

$$P_0 \propto (1/S_0)^2$$
$$\propto \left(\frac{1}{0\cdot 43\, anT}\right)^2$$

Some of the results at which we have arrived may be presented in numerical form by tabulating the relative transmitter powers for various speeds of signalling at

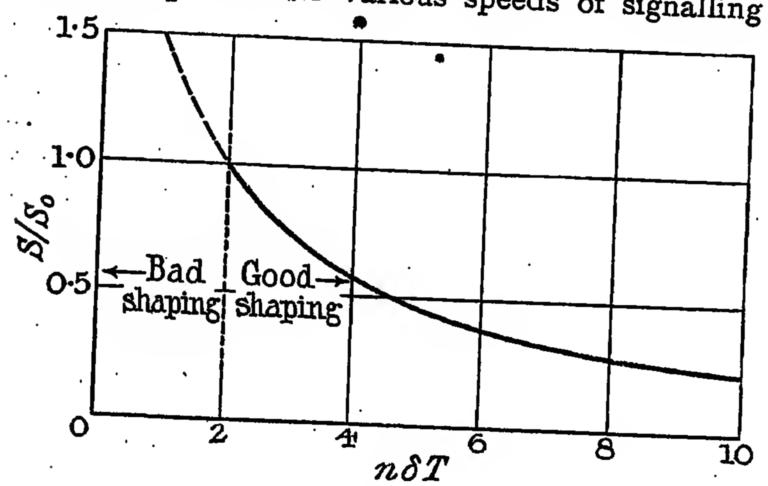


FIG. 9.

several specified *constant* decrements. This is done in Table 2 for the three wave-lengths already used in Table 1. The figures are arrived at as follows. At any one wave-length let P be the transmitter power producing in the receiver the E.M.F. E, which excites the oscillation actuating the relay when the amplitude A_0 is reached. Then

$$P \propto E^2$$
$$= KE^2 \text{ (say)}$$

where K is the transmitter power which produces unit E.M.F. in the receiving circuit at the particular wave-length. K is a factor depending upon the transmitter, the propagation between the stations, and the receiving aerial; it varies (in general) with the wave-length, but is independent of the speed of signalling and decrement of the receiver. Now we have seen that

$$E = A_0 \times \frac{2nL}{a} \times \frac{\delta}{1-\epsilon^{-n\delta T}}$$

Therefore

$$P = KE^2 = K\left(A_0 \times \frac{2nL}{a}\right)^2 \times \frac{\delta^2}{(1-\epsilon^{-n\delta T})^2}$$
$$= \frac{P_1}{(0\cdot 01)^2} \times \frac{\delta^2}{(1-\epsilon^{-n\delta T})^2} \quad \text{(say)}.$$

where P_1, the power required for low speed at $\delta = 0\cdot 01$, is used as a convenient arbitrary standard of reference.

Then
$$\frac{P}{P_1} = \frac{10^4\delta^2}{\left(1-\epsilon^{-\frac{1\cdot 25 n\delta}{w}}\right)^2}$$

where w = speed in words per minute = $1\cdot 25/T$.* From this expression the values of P/P_1 given in Table 2 have been calculated for speeds between 5 and 200 words per minute at the three decrements 0·01, 0·003 and 0·001.

(5) *Summary and discussion of results.*—We have seen that with long waves and fairly high speeds of signalling on the Morse code it may readily happen that the received current amplitude is far from the sensibly "square-topped" shape met with in land-line telegraphy and in early wireless practice; that the shaping depends on the product $n\delta T$ only, and that $n\delta T = 2$ is about the border line between bad and good shaping. At any wave-length, therefore, the higher the speed of signalling the higher is the smallest permissible decrement. The sensitivity, S, of the receiver (to the tuned

* Based upon the conventional standard five-letter word "Paris."

TABLE 2.

λ	Decrement	Max. speed ($n\delta T = 2$)	P/P_1 at the following speeds (w.p.m.) 5	10	20	50	100	200	Maximum ($n\delta T=2$)
m		w.p.m.							
1 000	0·01	1 880	1·00	1·00	1·00	1·00	1·00	1·00	1·34
	0·003	566	0·090	0·090	0·090	0·090	0·090	0·090	0·121
	0·001	188	0·0100	0·0100	0·0100	0·0100	0·0105	[0·014]	0·0134
5 000	0·01	380	1·00	1·00	1·00	1·00	1·00	1·04	1·34
	0·003	112	0·090	0·090	0·090	0·092	0·114	[0·198]	0·121
	0·001	38	0·0100	0·0100	0·0105	[0·0166]	[0·036]	[0·104]	0·0134
20 000	0·01	94	1·00	1·00	1·00	1·04	[1·39]	[2·70]	1·34
	0·003	28	0·090	0·091	0·102	[0·198]	[0·49]	[1·51]	0·121
	0·001	9·4	0·0105	[0·0139]	[0·027]	[0·104]	[0·35]	[1·24]	0·0134

P = transmitter power at speed and decrement stated.
P_1 = transmitter power at low speed with $\delta = 0\cdot 01$ at wave-length stated.
Figures in brackets are for speeds higher than the maximum for good shaping ($n\delta T = 2$).

continuous-wave signal E.M.F.), instead of being sensibly inversely proportional to the decrement δ is found to be a function again of $n\delta T$, viz.

$$S \propto \frac{1 - \epsilon^{-n\delta T}}{\delta}$$

and similarly the transmitter power, P, required, instead of being sensibly proportional to δ^2, is

$$P \propto \frac{\delta^2}{(1 - \epsilon^{-n\delta T})^2}$$

Since, however, $n\delta T$ may not be less than about 2 (and then $1/(1 - \epsilon^{-n\delta T})^2 = 1 \cdot 34$), it follows that, with any specified wave-length and decrement, the power required to give the maximum speed is only some 34 per cent higher than the power for indefinitely low speed. It is, however, already a common experience in wireless operation that higher speeds sometimes require much higher power, and this is explained in the terms of our analysis by its implication that at a given wave-length the same decrement should not be used for low and high speeds. A rise in speed calls for a rise in decrement, to preserve the shaping; and it is this accompaniment of the augmented speed which is mainly responsible for the increase of power required.

It has been assumed that the signal E.M.F. impressed in the low-decrement receiving circuit is of sensibly square-topped shape. This cannot in fact be the case, because the inertia phenomena we have been studying at the receiver must also occur at the transmitter, though probably in less pronounced degree. The effect of the neglected transmitter inertia could probably be allowed for fairly accurately by applying a suitable fractional multiplier to the actual receiver decrement; thus if we find, with square-topped incoming E.M.F., that $n\delta T$ may be reduced as far as 2, with the actual E.M.F. the corresponding minimum permissible value would certainly be greater than 2 (though probably less than 4).

Most receivers comprise more than one circuit tuned to the signal, e.g. the antenna followed by one or a succession of circuits associated in series. Usually one circuit has its decrement maintained much lower than the rest, in which case our analysis may be applied with substantial accuracy to that circuit. Where, however, a succession of two (or more) lowly damped circuits is used, even a square-topped E.M.F. in the antenna may produce in the second (and subsequent) lowly damped circuits an E.M.F. far from square topped. The present single-circuit analysis is then not accurately applicable.

The bad effect on the shaping of the recorded signals of the too large residuum of amplitude at the end of a space suggests two ways of improving the signalling conditions. One is to transmit a curbing signal during the whole or part of a space, the transmitted dot or dash being ended, not by mere cessation, but by a change of phase of 180° in the aerial oscillation. This would be somewhat analogous to curbed-signal working in submarine cables. The idea might be carried further in making the latter part (or the whole) of the transmitted dash weaker than the dot, so as to reduce or remove the inequality between $\dot{A}$ and $\bar{A}$ (Fig. 5). Another form of curbing, easier to accomplish though perhaps less effective in theoretical possibilities, may be applied at the receiver. This method is examined in Part II of the paper.

Thus far only the recording of Morse signals by some form of relay has been mentioned. The receiver transients at the beginning and end of a signal are in some circumstances of vital importance, also in the low-speed reception of Morse signals, and obviously in telephony. When a receiver is so fitted up that very fine control of tuning and retroaction is obtained, the decrement can be pushed to and held at so low a value that marked "ringing" of the signals heard in the telephone is observed, even at wave-lengths of only a few thousand metres. However low the signalling speed may be, the bad definition at the beginning and end of the dot or dash so distresses the ear of the operator that further reduction of decrement, despite some increase in signal strength, does not help him to distinguish the signals. Measurements of these very low decrements—which are not easy to determine experimentally—are now in progress at Cambridge, and will, I hope, be published shortly.

Part II.—Receiver Curbing.

(6) *The process of curbing.*—When once the amplitude during a dash has reached the operative value A_0,

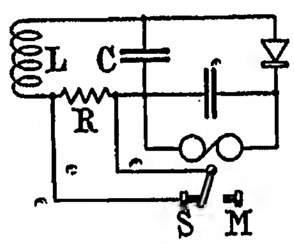


Fig. 10.

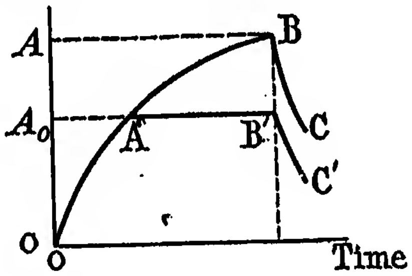


Fig. 11.

nothing is gained by allowing it to rise further; while in so far as it does rise further the residuum at the end of the subsequent space becomes more troublesome. Since the relay closes or opens a contact as soon as the operative amplitude is reached, it is feasible to make it introduce automatically at this instant additional impedance—preferably resistance—into the circuit, so curbing further growth of amplitude. Thus in Fig. 10, LC is the low-decrement receiving circuit, and contains a resistance, R, which is short-circuited when the relay spaces but is not short-circuited when the relay marks. As soon, therefore, as the operative amplitude has been reached, further growth is checked by the increase of decrement introduced by R; and if R is of suitable value the amplitude can be thereafter maintained at or just above the operative amplitude, and this whether the mark constitutes a dot or a dash of any length. The amplitude then follows the curve OAB'C' (Fig. 11) instead of OABC, and the conditions during the space following a dash are no different from those during the space following a dot. The advantage as regards uniformity is obvious.

If the curbing action is suitably prolonged, so that the resistance R (Fig. 10) remains in circuit during a considerable part of the space following the mark,

there is the further advantage that the amplitude falls more rapidly during the space than it otherwise would. It would be possible to arrange for this in Fig. 10 by utilizing well-known devices to make the relay dwell on its marking contact, and providing a separate relay for actuating the recorder; but other methods, of the type described with reference to Fig. 15, are also feasible.

(7) *The improvement obtainable.*—The improvement in terms of speed and power conferred by curbing will be greatest when the amplitude is curbed precisely to the operative value A_0; when the decrement of the circuit apart from curbing is negligible; and when the added decrement is retained throughout sensibly the whole of the space. Retaining, as in Section (2), the symbol $\dot{A}$ for the uncurbed amplitude at the end of during the curbed part of the mark

$$A = A_0;$$

and during the space

$$A = A_0\epsilon^{-n\delta_c t}$$

where t is measured from the beginning of the space and $\delta_c = 1/(\alpha nT)$.

When $\alpha = 0 \cdot 60$, our test letter "1" is shown in Fig. 12; and when $\alpha = 0 \cdot 75$, in Fig. 13. The signals are clipped as regards the marks; for with this curbed working the ends of the marks synchronize precisely with the rise of the key at the transmitter, whereas the beginnings are necessarily delayed. But, as already pointed out in reference to the uncurbed working, this

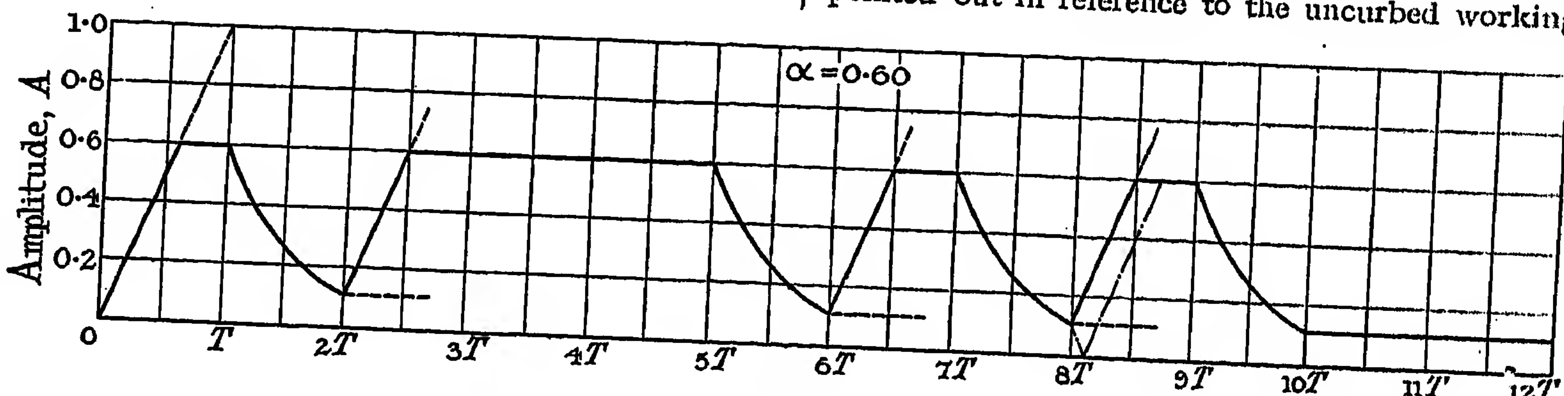


Fig. 12.

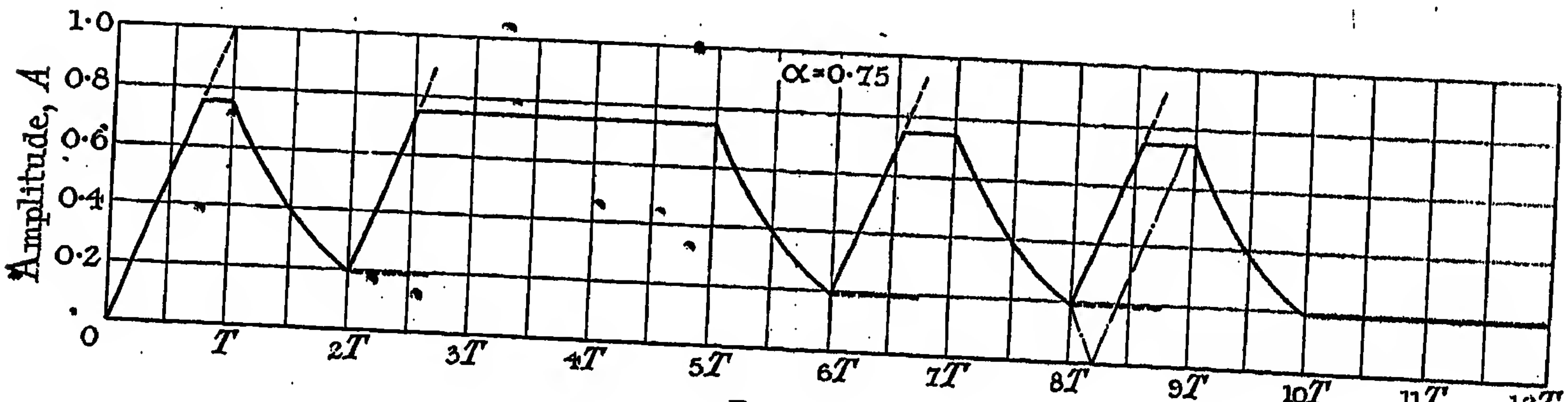


Fig. 13.

a dot, $A_0 = \alpha\dot{A}$, and writing δ_c for the decrement introduced by the curbing action, we have

$$\dot{A} = \lim_{\delta=0}\frac{E}{2nL} \times \frac{1-\epsilon^{-n\delta T}}{\delta} = \frac{E}{2L}T$$

$$\dot{A}_s = \bar{A}_{s_0} = A_0\epsilon^{-n\delta_c T} = \alpha\dot{A}\epsilon^{-n\delta_c T} = \frac{\alpha E}{2L}T\epsilon^{-n\delta_c T}$$

Now to keep amplitude constant at A_0 after curbing begins, δ_c must be given the value making

$$A_0 = \frac{E}{2nL} \times \frac{1-\epsilon^{-n\delta_c t}}{\delta_c} \quad \text{when } t = \infty$$

$$= \frac{E}{2nL\delta_c}$$

Therefore

$$\delta_c = \frac{E}{2nLA_0} = \frac{1}{\alpha nT}$$

During growth, therefore, $A = \dfrac{E}{2L}t$

where t is measured from the beginning of the mark; does not impede the reading of the tape; the shortening is the same in absolute amount for dot and dash; and moreover, the dot as recorded could be lengthened artificially if desired.*

The higher α is made, the greater is the sensitivity of the receiver, but the more pronounced becomes the discrepancy between a first and a subsequent dot. For the purpose of comparison with uncurbed working, some examples of uncurbed and curbed records, judged of equally good quality, must be compared. For this purpose Fig. 6 and Fig. 12 are taken as equally good and of high quality, and Fig. 7 and Fig. 13 as equally good though of poor quality.

For Fig. 6 we found [Section (4)]

$$\frac{E}{A_0} = 2nL \times \frac{\delta}{\alpha(1-\epsilon^{-n\delta T})} = 2L \times \frac{1}{0 \cdot 303\, T}$$

(because $n\delta T = 2$ and $\alpha = 0 \cdot 70$)

* It is interesting to reflect that Morse signals would theoretically be very nearly wholly determinate even if nothing were known of them except the instant of termination of each mark; the only ambiguity being that 4 units of interval might signify either a short space (1) followed by a dash (3), or a letter space (3) followed by a dot (1). The instant of termination is recorded accurately in our curbed régime.

For Fig. 12 we have found

$$\frac{E}{A_0} = 2nL \times \frac{1}{\alpha nT} = 2L \times \frac{1}{0 \cdot 60\, T}$$

(because $\alpha = 0 \cdot 60$)

Hence for equal speeds

$$\frac{\text{power, uncurbed}}{\text{power, curbed}} = \left(\frac{0 \cdot 60}{0 \cdot 303}\right)^2 = 4 \cdot 0$$

or for equal powers

$$\frac{\text{speed, curbed}}{\text{speed, uncurbed}} = \frac{0 \cdot 60}{0 \cdot 303} = 2 \cdot 0$$

Taking good signals in each case, therefore, the curbed régime shows a marked superiority over the uncurbed.

The comparison between Fig. 7 and Fig. 13, calculated in precisely similar fashion, is as follows. For equal speeds

$$\frac{\text{power, uncurbed}}{\text{power, curbed}} = \left(\frac{0 \cdot 75}{0 \cdot 39}\right)^2 = 3 \cdot 7$$

and for equal powers

$$\frac{\text{speed, curbed}}{\text{speed, uncurbed}} = \frac{0 \cdot 75}{0 \cdot 39} = 1 \cdot 9$$

Hence, comparing equally good signals of inferior quality, nearly the same superiority is shown by the curbed over the uncurbed régimes.

(8) *Application to working conditions.*—In actual working it is not possible wholly to satisfy either of the ideal conditions assumed in the last section; viz. zero decrement until the curbing is applied, and curbing retained during just the whole of the space between marks. The importance of these practical departures from the ideal régime is now examined.

During a mark before curbing the amplitude grows with time as

$$A = \frac{E}{2\,L} \times \frac{1 - \epsilon^{-n\delta t}}{n\delta}$$

whereas if $\delta = 0$ it grows as

$$A = \frac{E}{2\,L}\, t$$

These two growths are plotted in Fig. 14. The amplitudes diverge considerably—say by more than 5 per cent—only when $n\delta t$ exceeds (say) $0 \cdot 155$. If the operative amplitude is reached at $t = 0 \cdot 60\, T$ as in Fig. 12, the divergence is thus unimportant if

$$n\delta \times 0 \cdot 60T < 0 \cdot 155$$

i.e. $$\text{if } \delta < \frac{0 \cdot 26}{nT}$$

Hence at (say) 100 words per minute ($T = 0 \cdot 0125$ sec.) there is no important distinction to be made between decrements of zero and

$0 \cdot 00007$ when $\lambda = 1\,000$ m
$0 \cdot 00035$ when $\lambda = 5\,000$ m
$0 \cdot 0014$ when $\lambda = 20\,000$ m

If it is not practicable in any particular case to obtain such a low decrement as is sensibly equivalent to zero according to the above relation, a correction for the divergence of the two lines in Fig. 14 should be applied. Thus at 100 words per min. when $\lambda = 5\,000$ m if, for example, $\delta = 0 \cdot 001$ instead of zero (or $< 0 \cdot 00035$), the E.M.F. would have to be increased

$$\frac{0 \cdot 60\, n\delta T}{1 - \epsilon^{-0 \cdot 60\, n\delta T}} = \frac{0 \cdot 45}{1 - \epsilon^{-0 \cdot 45}} = 1 \cdot 24 \text{ times}$$

that is, the transmitter power would have to be increased $(1 \cdot 24)^2 = 1 \cdot 54$ times, so reducing the ratio (power, uncurbed)/(power, curbed) from $4 \cdot 0$ or $3 \cdot 7$ to about $2 \cdot 5$. It may well be that with wave-lengths such as 5 000 m and under, it is not feasible to use the indefinitely low decrements, and some such allowance is necessary. But with long waves, such as 10 000 m and upwards, the indefinitely low decrements of the ideal régime seem to be realizable.

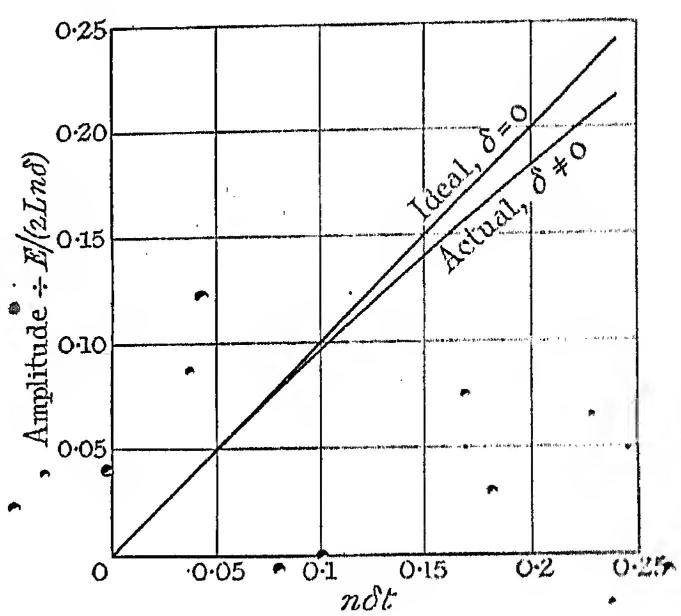


FIG. 14.

The retention of full curbing throughout sensibly the whole of the spacing epoch between marks does not present much practical difficulty, and one way of effecting it electrically is shown in Fig. 15. When the amplitude in the oscillatory circuit LC has grown to the operative value, the relay tongue moves from S to M. While it was at S the grid potential of the curbing triode was $-b_1$ (where b_1 is the E.M.F. of battery B_1), which is sufficient to prevent the coupling M_1 from introducing any damping into LC. On contact being made between tongue and M, the grid potential immediately rises to $-(b_1 - b_2)$, thereby allowing anode current to flow in the curbing triode and damping LC to an extent controllable by M_1. When the incoming signal ceases, the tongue returns to S, and the potential of the grid falls towards $-b_1$ according to the expression

$$-(b_1 - b_2)\,\epsilon^{-\frac{t}{C_1R_1}}$$

These changes are portrayed in Fig. 16. A transmitted mark starts at O and ends at B. At A the relay moves to mark, and at B returns to space. During the space, full damping obtains from B to C, because the triode is operating on the straight, steep, part of its charac-

teristic curve. From C until the end of the space D there is a short transition epoch corresponding to the change, FG, of grid potential. When the grid potential is lower than OG, the damping is sensibly nil. At D the transmitter comes on again, actuating the relay anew at E. By making both b_1 and b_2 large enough, we cause the transition range FG to be swept through as quickly as desired.

With any chosen voltages b_1, b_2 and b_3, the grid is made to pass through the transition range of potential FG at the right time by adjustment of the time-constant C_1R_1. This, therefore, is an adjustment which must be altered when the speed of signalling is altered, but it depends on that alone. There is one other adjustment dependent on the speed of signalling, viz. the mutual

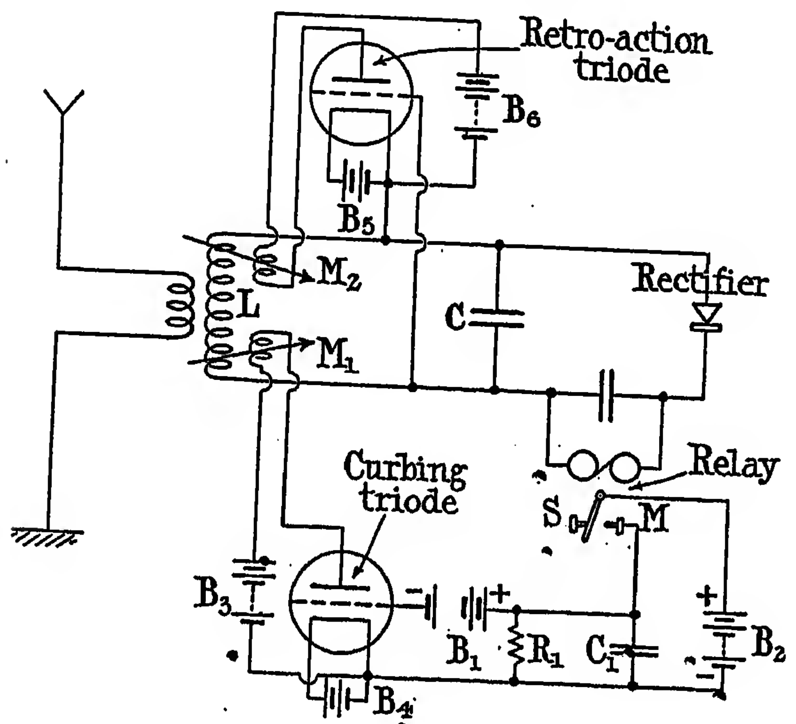


FIG. 15.

inductance M_1, which must be set to give the correct damping

$$\delta_o = \frac{1}{anT}$$

In Fig. 15 is shown for the sake of completeness a retroaction triode with variable mutual inductance M_2 for reducing the uncurbed decrement of LC to a suitably low value. The rectifier shown without detail would, of course, ordinarily be a thermionic triode rectifier, with some form of amplifier between it and the relay. The six batteries B_1 . . . B_6 are all shown separate for the sake of simplicity of diagram. In practice only three batteries would be wanted, viz. ($B_2 = B_3 = B_6$) in common, ($B_4 = B_5$) in common, and B_1. If the well-known "R" pattern of triode were used, suitable voltages might be about

$$b_2 = b_3 = b_6 = 120\text{ V}$$
$$b_4 = b_5 = 3\cdot 6\text{ V}$$
$$b_1 = 120\text{ V}$$

With these values, the transitional grid-potential range FG would be about -10 to -15 V, so that the time-constant C_1R_1 would be adjusted to make the grid potential fall from 0 to -15 V in time T (from B to D in Fig. 16). At 100 words per minute, therefore,

$$-[120 - 120\,\epsilon^{-0\cdot 0125/(C_1R_1)}] = -15$$

i.e.
$$0\cdot 0125/(C_1R_1) = 13$$

or $C_1R_1 = 0\cdot 1$ (say $C_1 = 1\mu$F and $R_1 = 0\cdot 1$ megohm).

The time CD covering the range FG = 5 V is then about 0·004 sec., which is probably sufficiently brief.*

It is not suggested that the particular arrangement of Fig. 15 is the best means of realizing the curbed régime we have studied; it illustrates one of various

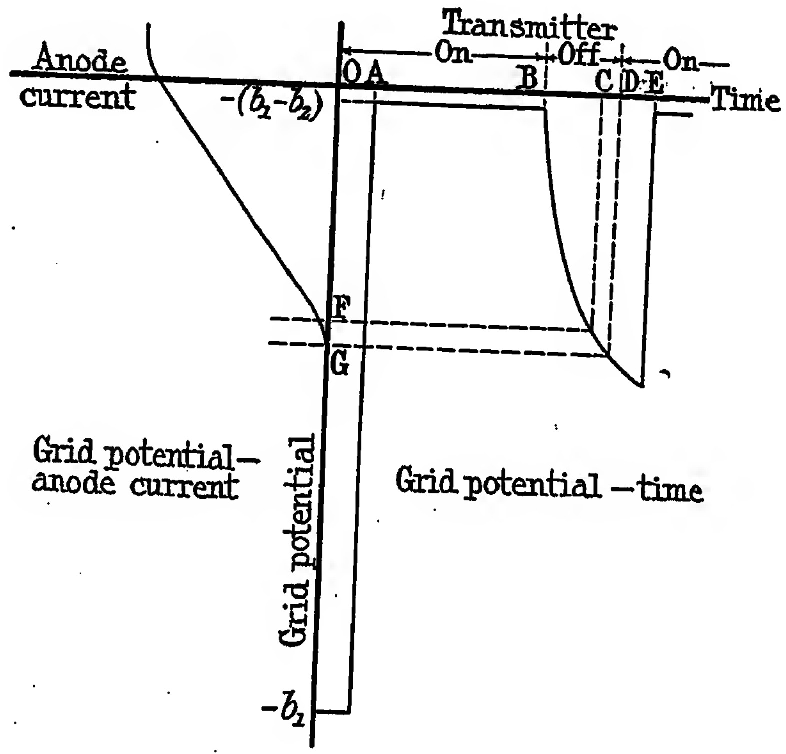


FIG. 16

possible means to that end. The various relaying and recording devices already applied to cable telegraphy would provide alternative schemes. The author's primary concern in Part II of the paper is to point out that the curbed régime offers important advantages over the uncurbed, and appears to be a practicable system. Despite the difficulties introduced by atmospheric disturbances and opacity—in some degree, because of them—the wireless art is now reaching a maturer stage in which the working speed is becoming as direct a measure of the worth of a wireless route as it is of the worth of a cable route. The time is ripe, technically and economically, for higher speeds. It may well be, as Dr. Eccles has recently suggested,† that this advance will ultimately involve a radical change in the type of signal transmitted; meanwhile, leaving the costly transmitter as it is, we shall do well to procure from the humble receiver the best service that an understanding of the latter's functions can command.

* The presence of full damping during the final stages of the space is, of course, of less consequence than during the initial stages. Thus in Fig. 12 the fall in amplitude during the first fifth of the space is 0·170, and during the last fifth is 0·044.

† "Studies from a Wireless Laboratory": discourse delivered at the Royal Institution, 18th April, 1923.

Discussion before the Wireless Section, 5 December, 1923.

Major A. G. Lee: The paper comes at a very opportune time, seeing that the problems of high-speed wireless telegraphy are very closely associated with the successful commercial operation of high-power stations. The practice has grown up, following the lead set by the American group of telephone engineers, of referring to a receiver in terms of the width of its resonance curve or band. This bears a definite relation to the operation it has to perform, viz. the reception of a carrier wave, modulated telegraphically at a certain speed. It may, therefore, be of interest to compare this view-point with that outlined in the paper. It is well known that a square-topped telegraph signal can be resolved into a Fourier series consisting of a fundamental sinusoid together with a number of harmonics. If, now, we neglect the harmonics as being relatively unimportant and suppose a carrier wave to be completely modulated by the fundamental of the telegraph signal, we obtain as the product the carrier wave together with two side frequencies, each differing from the carrier frequency by the amount of the fundamental of the telegraph signal. In order to receive this signal without appreciable distortion, the receiver must have a resonance curve wide enough to admit a band equal to twice that of each side band. If the dot frequency of the telegraph signal is $1/(2T)$, the side frequencies will be $n + [1/(2T)]$ and $n - [1/(2T)]$, and the width of band necessary for approximate distortionless reception will be $1/T$. Now $n\delta$ is twice the width of the resonance curve at the point where $I = 0\cdot 54 I_r = 2(1/T)$, i.e. $n\delta T = 2$. So that, neglecting harmonics of the fundamental, which will to some extent contribute to the shape of the received signals, this criterion that the receiver should have a band width of $1/T$ is the same as the author's condition of $n\delta T = 2$, for the case where the width of the resonance curve is taken at $I = 0\cdot 54 I_r$. Modern receiver practice tends towards a vertical-sided resonance curve, so as merely to include the side-band frequencies required and nothing else, and in practice there is considerable departure in shape from the theoretical resonance curve given in Fig. 3, which has a narrow top and wide feet. There may be some advantage in having a receiver with two peaks with a hollow in the middle, as this would compensate to some extent for the distortion produced by the antenna resonance curve at the transmitting end. It is well known that if one has a multi-stage tuned high-frequency amplifier, or a multi-stage tuned note amplifier the more stages one adds the narrower becomes the resonance curve of the whole apparatus. If one could start off with a square-topped wave in the transmitting antenna, the receiver may reduce its band to $1/T$, but in practice the low-decrement transmitting antenna comes in as part of the chain, starting from the square-topped telegraph signal at the transmitting key and finishing at the receiving telephone. With the low-decrement transmitting stations in use at the present time it is probable that the transmitting end is equivalent to 2 or 3 stages in this chain, so that for a given $1/T$ the receiver band has to be widened considerably to allow for the fact that part of the low-decrement effect has been used up at the transmitting end. In other words, the narrower we make the band received the more distortion there is. Therefore, if we have distortion at the transmitting end, the receiver must have relatively less distortion, so that the overall distortion comes within the allowable amount corresponding to the author's criterion of $n\delta T = 2$. The disadvantage of widening the receiver band is that atmospherics are let into the chain at an intermediate point, viz. between the transmitter and receiver, and hence do not have the whole battery of low decrements available against them. It is not, perhaps, sufficiently widely recognized that by the use of different marking and spacing waves the transmitting antenna can be made to change instantaneously at full amplitude from one frequency to another, giving the much-desired square-topped wave in the antenna. The use of this system would permit of a narrower band being employed at the receiver, with consequent greater selectivity against atmospherics. The suggestion to employ curbing at the sending end, or to signal by change of phase of 180 degrees, is of interest. I considered this proposition some time ago, but came to the conclusion that there were many difficulties, and that the current in the antenna would not present the square-topped outline that it does with the marking and spacing wave system. In any valve transmitting system in which the aerial is allowed to have any coupling whatever with the master oscillator, it will control the frequency of oscillation to some degree. If, now, the phase of this control is altered by 180° suddenly, violent frequency and amplitude fluctuations are liable to be produced. With regard to the suggestion to employ curbing at the receiving end, I am rather doubtful as to its effect, because the wireless problem differs from the cable problem in that atmospherics are present as well as signals. In the curbing system proposed, the decrement is increased over a considerable portion of the telegraphic cycle, a process which inherently renders the system more liable to attack from atmospherics. An alternative form of curbing would be to put the whole system out of action momentarily at the conclusion of a mark, by short-circuiting all the condensers of the set, after which the receiver would resume its normal low-decrement operation. On one point mentioned by the author, viz. the constancy of transmitter frequency, I should like to add some details: For a speed of 100 words per minute a band width of 80 periods for the whole chain (transmitter to receiver) is necessary. Now if the transmitter varies in mean frequency the receiver has to be tuned with a wider band to allow for these variations. I have had measurements made of the variation of frequency of existing stations, and find that the variations are approximately as follows, depending to some extent upon wind and weather conditions at the transmitting station:—

	Variation in frequency, p.p.s.
Most-constant alternators	10
Less-constant alternators	30
Separately-excited valve sets ..	30
Plain aerial valve sets	50
Plain aerial arc sets	160

The handicap due to this cause in receiving 100 words per minute is fairly obvious. There is no reason why the separately-excited valve set should not improve upon the figure given, but it demands perfect screening of the master oscillator from the effects of the aerial swinging, as well as good design in the oscillator itself and the voltages supplied to it. Another cause of variation in width of band in the case where note tuning is employed, lies in the local heterodyne at the receiving end. It is equally important that this shall be free from variation of frequency, and the causes of variation are the same as those affecting a transmitting oscillator.

Mr. E. B. Moullin: The paper is very interesting to me because it imposes a lower limit on the decrement of circuits for which n and T are fixed. Early next year I shall be reading a paper before the Wireless Section on "Atmospherics and Their Effect on Wireless Receivers," in which it will be shown that for slow signalling the best way to reduce the effect of atmospherics is to reduce the decrement indefinitely. If the speed of signalling is taken into account, but no regard paid to the shaping, it can be shown that a circuit for which $n\delta T = 1$ is about 40 per cent more immune from disturbance than one for which $n\delta T = 2$, and that there is little to be gained by reducing $n\delta T$ below, say, $\frac{1}{2}$. If $n\delta T$ must be greater than 2, I think that the transmitter power will have to be increased by more than is calculated in the paper, in order that the signals may still hold their own against atmospherics. If, as the author suggests, the transient effect of the transmitter may force us to keep $n\delta T$ greater than 4, it will therefore necessitate a very great increase of power. It seems important to examine whether $n\delta T$ is limited to 2 or 4, and I have attempted to calculate how much the transmitter will affect the shaping. As I have had no time to work out the problem in terms of the constants of the transmitter, I have supposed that the received E.M.F. is given by $e = E(1-\epsilon^{-bt}) \sin pt$ while the transmitting key is depressed, and by $e = E'\epsilon^{-bt} \sin pt$ after the key has been raised. Both the rise and the fall of current will then be delayed more than is considered in the paper. For instance, if $n\delta T$ equals 2 and 4 for receiver and transmitter respectively, I find that the first dot leaves a residue which is 50 per cent greater than if the received E.M.F. had been square-topped: the dot is also more displaced and slightly more clipped. Transmitting antennas of recent construction have very small decrements; $n\delta T$ may be approximately equal to 4 and then the shaping would not be good in a receiver for which $n\delta T = 2$. A small transmitter decrement will necessitate an increase of power in addition to the 34 per cent which has to be added because of the receiver decrement, for we must make the transmitter power sufficient to force the transmitter current up to a specified amount in a given time. If $n\delta T = 2$ both for transmitter and receiver, we should have to increase the power by 75 per cent in order to get operating signals, and we must then provide a further margin of power so as to obtain satisfactory shaping. The transmitter decrement must still be considered when we are using a "curbed receiver," for even if its decrement is zero when uncurbed the current will not rise uniformly and, after curbing, it will fall at a rate that depends mainly on the transmitter. A great improvement would be effected if we could curb the transmitter. To obtain good shaping with the curbed system presented in the paper it may be necessary that the transmitter should have $n\delta T > 2$. Much of the bad shaping is caused by the dash lasting longer than the dot; since the current rises to a higher value during a dash than during a dot it leaves a much bigger residue on which to build the ensuing sign. If we shorten the transmitted dot I think that we shall get a received record which is a much closer approximation to standard Morse. I have shortened a dash from three units of time to two and have drawn out the letter "l" as received in a circuit for which $n\delta T = 1 \cdot 5$ (see Fig. A). For ease of comparison the record of Fig. 6 of the paper is reproduced in the upper part of my figure (the dash of Fig. 6 has been reduced so as to bear the same ratio to the first dot as that obtaining in my record). The quality of the shaping appears to me to be equal to that of Fig. 6, and I think that the ratio of dot to dash makes it a better approximation to correct Morse. The clipped dash provides a simple method of lowering the limit of $n\delta T$ from 2 to $1 \cdot 5$, and it is also equivalent to a certain increase of signalling speed. Many of the difficulties caused by transmitter and receiver decrement

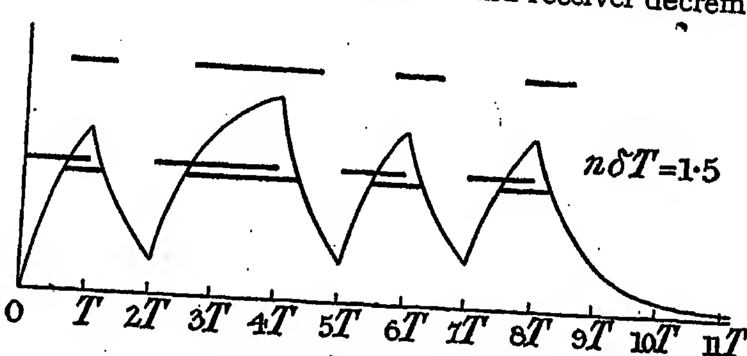


FIG. A.

might, I feel, be overcome by transmitting dots and dashes of equal duration but on slightly different wave-lengths. Two receivers would be used, one for dashes and one for dots, and the two recorders would be arranged to mark in parallel lines on the same tape. If the change of wave-length from dash to dot or space is made small the transient effect at the transmitter will be very small, especially if the change can be made at the instant of zero current. The average space between the marks on either receiver will be greater than with the present system and neither receiver is called upon to register marks of varying duration. The space between a dot and a dash is not required, and that combined with a short dash is equivalent to a great increase of speed. The letter "l" as recorded with the suggested system would appear on the tape thus: —_— —. The letter "l" now occupies 8 instead of 12 units of time, and the word "Paris" will occupy 30 units instead of 41. I am of opinion that the system which I have outlined would permit of the use of very small decrements, and for a given decrement an increase of 25 per cent in the signalling speed. It may also be noticed that with low-speed signalling almost perfect secrecy could be obtained by widely separating the dot wave-length from the dash wave-length; even though the dots of the desired message

could be picked up it would be necessary to search through every other detectable message in order to pick up the missing dashes.

Professor G. W. O. Howe: It seems a great pity that, having escaped from the serious limitations of the submarine cable by being provided with a medium and method of signalling which obviate all the troubles due to the conductor resistance and the specific inductive capacity of the gutta-percha, we introduce very similar limitations by the design and operation of our receiving apparatus. On comparing a figure like Fig. 8 with the ordinary siphon records from which submarine cable operators have to read, one would be inclined to call it a very good signal. Nobody looking at that curve could mistake it for anything else but an "l." As I have sat here this evening the idea has been forced on me that we are adopting a fundamentally wrong method of reading these signals in having to use non-proportional apparatus which is only operated by currents exceeding a certain limiting value. If we could only get that zig-zag signal of Fig. 8 reproduced in some way by some siphon recorder, even badly, we should still get signals enormously better than those that the submarine cable operators consider good. Those familiar with an ordinary submarine cable tape will know that the dots and dashes vanish entirely from the signal as recorded. The operator reading the letter "h," for instance, sees no sign of the four dots. He merely knows that there were four dots there because there is a hump which looks about four dots long. It seems to me that research should be directed to the development of some recording apparatus which will work in a somewhat similar manner to the siphon recorder and give a record of the "humps" in Fig. 8.

Mr. J. E. Taylor: In Part II, in connection with curbing, the author proposes to introduce a resistance into the receiver circuit which is normally short-circuited by the tongue of a relay on the spacing stop. He says that it is necessary to bring the current up to the marking value, and for making a dash, for instance, to retain it at that value until the dash has terminated. In my view it is not necessary to retain the current at the same value as that which is required to detach the relay tongue from the spacing stop. In operating a relay a certain strength of current is required to throw the tongue over, but usually a very much smaller current will retain the tongue on the marking stop. I think, therefore, that the author might very well allow his decremental resistance to become operative at the beginning of his signal. The delay action introduced in the diagram shown in Fig. 15 is, in my opinion, not really necessary. These considerations also lead me to think that it would be advantageous, in spite of the difficulties at the transmitter, to try to do as much curbing as possible at the transmitter. This would result in less expenditure in power, and, in addition, the tendency to interfere with other stations would be reduced.

Mr. F. P. Best: Under the supervision of the author I have been engaged on the investigation of the so-called "optimum decrement of a receiver" under conditions which exist in ordinary low-speed telegraphy as received by an operator. In this investigation of the optimum decrement, experimental evidence alone must indicate the values to be expected, for it is not possible to apply mathematical analysis as in the case of automatic reception. The low decrements had to be produced in such a manner that they would remain constant for some considerable period of time—a thing not easy to accomplish. Not only had that to be done, but once having obtained these low decrements their measurement becomes a matter of considerable difficulty, because the decrement itself, where retroaction by means of a triode is used, varies considerably with the actual amplitude of the current in the low-decrement circuit. These two difficulties were, however, overcome and measurements of this optimum decrement were made on six wave-lengths. The actual optimum decrement chosen is that decrement which makes the signal most easy for an operator to distinguish, and is, of course, a compromise between the actual loudness of the signal and the amount of ringing that can be permitted. The wave-lengths considered varied from 4 350 m (Ongar) to 23 450 m (Bordeaux), and the optimum decrements ranged from about 0·0018 for Ongar to 0·0083 for Bordeaux. Thus if we select a rate of signalling of about 25 words per minute, which was approximately the rate at the moment these measurements were taken, we obtain a value for $n\delta T$ of about 5. That is to say, if an operator is to distinguish without much difficulty the signals which are being transmitted, a decrement cannot be allowed which will bring the value of $n\delta T$ lower than 5. Another thing that seemed worthy of notice in this investigation was the value of $n\delta$ itself. The precise value of T above (= 0·05 for a speed of signalling of about 25 words a minute) did not seem to make a great deal of difference to the value of $n\delta$ and probably if the speed of transmission dropped to more than half that rate the decrement could not be appreciably lowered, since it appeared that below a certain fixed decrement (dependent upon the wave-length) the amount of ringing made it quite impossible for the operator to distinguish the signal, however low the speed of transmission might be. This value of $n\delta T$ compares unfavourably with the figure of 2 suggested by the author; but when it is remembered that in the case of the relay we are dealing with an almost physically perfect instrument, and that in the case of the ear we are dealing with an instrument not by any means physically perfect, this discrepancy is not to be wondered at.

Mr. R. E. H. Carpenter: I entirely agree with Prof. Howe that the signals which the author regards as unrecordable are very excellent signals indeed. It does seem remarkable that with this striving after a low value for $n\delta T$ the expedient of using a proportional recorder not working between fixed stops has not been mentioned by the author. I have already emphasized here the importance, in my view, of using such a recorder from the point of view of discrimination between signal and atmospheric. If one uses a proportional amplifier and a recorder which is also approximately proportional, and gives some approximation to a time/current graph of what is being obtained from the receiver, one can do a very great amount of visual discrimination between signal and atmospheric on the tape. The present paper

seems to me to bring out clearly a further advantage of such a recorder.

Professor E. W. Marchant: I have had the opportunity of seeing Mr. Best's results, and I think that he has left out one most interesting thing in his contribution to the discussion. Not only has he managed to determine the optimum decrement, for the two stations that he mentioned, but he has also obtained them for three American stations.

Mr. C. F. Elwell: Before the days of the triode, I was using on some high-speed work a system known as the Pedersen system. That system was quite capable of transmitting and recording 200 words per minute, and it might be of interest if I gave a résumé of how receiving was done, in view of this figure of $n\delta T$. The receiver consisted of the ordinary oscillating circuit and a detector which consisted of a piece of graphite, usually lead pencil, and a piece of galena. The received current passed through an Einthoven string galvanometer consisting of very fine gold wire, part of which was smoked in order to give a larger shadow. The movements of the wire were recorded on photographic tape, and we carried out tests up to 200 words a minute, at wave-lengths of 2 000 to 8 000. The signals were quite square-topped when there were few atmospherics. The Pedersen system had to be entirely abandoned because we could not eliminate atmospherics. We later employed the three-electrode amplifier, which was developed about 1911, and did our recording on the telegraphone, another invention of Poulsen. The use of some of this old apparatus might be revived in view of the attempts to-day to get really well-shaped high-speed wireless signals.

Major H. P. T. Lefroy: It seems to me that the author is rather pessimistic in regard to possible speeds of signalling with circuits of normal damping. In 1919 the Signals Experimental Establishment worked from Aldershot to Woolwich at a speed of 700 words per minute, on a wave-length of about 1 000 m, and the signals were clear. For such a high speed the type of recorder used was one of those in which the receiving tape, impregnated with a compound of iodine, changes its colour when the received signals cause current to pass through it. With regard to very long wave-lengths, I have found no difficulty in working at a speed of 240 words per minute on a 50 km wave-length. That speed indicates a very high damping factor, if we use the author's formula $n\delta T = 2$, viz. $\delta = 0 \cdot 067$, which, since the inductance of the tuned circuit was about $0 \cdot 5$ henry, indicates an effective resistance of about 400 ohms; but such a resistance seems improbable, in view of the fact that, whilst desired signals were being recorded faultlessly on the tape, the receiving circuit was exposed to severe interference from Wheatstone automatic. The recorder that I was using then was of the trigger-amplifier type, which appeared to be a good type to use, because it was possible, by trial and error, to adjust the bias of the relay in such a way that the space (on the tape) for a "dot" and for a "space" was the same, and, when so adjusted, clear signals were recorded; by this method only the crests of the signals are recorded, and the curves of growth and of decay are not shown on the tape. I have been much impressed with the extraordinary parallels between the ideas in the present paper and those in Mr. Sutherland's contribution to the discussion on "Loud-Speakers" on the 29th November last at the Joint Meeting of this Institution and the Physical Society. Mr. Sutherland showed a graph of the sequence of syllables, in connection with reverberation and the absence of damping in a room. That graph was practically the graph shown on pages 195 and 196 of the present paper. He pointed out that, if a room is not sufficiently damped, the number of words per minute must be reduced to suit that room. He also pointed out how useless it was to increase the intensity of speech if a room was not sufficiently damped, to both of which ideas the author has been calling attention this evening in connection with high-speed signalling.

Professor C. L. Fortescue (*communicated*): To anyone who has given any consideration to the problems of high-speed reception the paper is full of interest. But I think that although little has been published on this subject, far more work has been done than the author's opening remarks seem to imply. I believe that experiments were carried out some years ago in which the resistance of a receiving circuit was so far reduced that hand-speed Morse was unintelligible with a wave-length of 15 000 m. Telephony practice has led to many people looking upon this problem from the "side-band" point of view, and this immediately suggests that one way in which it might be possible to use ultra-selective circuits would be to work with only one "side band" and to supply the "carrier wave" at the receiving station. The author has assumed an incoming signal of sinusoidal form, whereas actually it must be one of gradually increasing amplitude. This does not appreciably alter the numerical results with the low-decrement circuits. There is one aspect that the author has not considered, viz. signalling by very small frequency-changes. It would appear that the difficulties in the way of using very low decrements would be still more serious than in the case assumed in the paper. Finally, I should like to ask what is the object of using circuits of decrement $0 \cdot 0001$. The adjustment of the reaction is infinitely difficult, the gain in signal strength is unimportant and the immunity from shock interference is not large. In fact, the incoming signal is already a "shock" to such a system.

Mr. L. B. Turner (*in reply*): Several points have been raised in more or less similar form by more than one speaker, and I shall deal with these first. It is suggested that I have overstated the difficulties of high-speed wireless recording in that I have investigated the case of relay rather than siphon recorder working, and that my assessment of 2 for the border value of $n\delta T$ between good and bad recording is too high. Now the paper makes no pretence to determine actual values of power required or speed obtainable in any particular case, but it investigates how power and speed depend upon damping and upon each other. Just as the practical performance of a submarine cable must be worked out by calculating arrival curves,* so, I point

* As done in Dr. W. H. Malcolm's admirable "Theory of the Submarine Telegraph and Telephone Cable" [Benn Bros., 1917].

out, must we endeavour to determine what corresponds to these arrival curves in the wireless receiver. These curves are found to depend upon the product $n\delta T$, and the three examples given in Figs. 6, 7 and 8 may be used in estimating the performance in all cases where this product has the assigned values. This is so whether the recorder is of the proportional type often used in cable telegraphy, or whether of the relay type always used on land lines, often used on cables, and at least hoped for by wireless engineers who are (like myself) optimistic enough to look for high speeds and automatic re-transmission.

In common with Prof. Howe, I lament the appearance of inertia effects in modern wireless. I agree with him and with Mr. Carpenter that a proportional recorder would often give readable signals when the relay signals which I have specially investigated would not be readable (or automatically re-transmissible). Of Fig. 8 (for $n\delta T = 1$) I did not write, however, as Mr. Carpenter suggests, that it represents unrecordable signals, but that "no approach to uniformity can be obtained whatever value is given to A_0." I set my standard of "shaping" at $n\delta T \nless 2$; I think it would distress a land-line telegraphist (whom wireless engineers should try to please) if it were put much lower than 2. It is open to anyone, however, to adopt any other figure he may find appropriate to his particular recording instrument, and still utilize the analysis that I have given. Let him not forget, however, that he has to cope with atmospherics with which my too-excellent curves are not defiled.

Major Lee and Prof. Fortescue refer to the "sideband" view taken by wireless telephonists, and the former definitely applies this criterion of distortion to Morse signalling. Now while telephone theory has commonly contented itself with analysis of the steady state—admittedly often far from reality, but yielding tolerably good practical rules as regards volume and clarity of speech signals—it is not possible to regard Morse signals as periodic. The series of dots from a Wheatstone transmitter when the tape has run out can be so treated, but not the irregular succession of dots and dashes when the tape is there. A resonance curve, whether of a single circuit as in Fig. 3, or with the steeper sides of a complex filter circuit, is a curve showing what will happen when the signal has been sustained for a sufficient period to enable the steady state to be sensibly reached. Its sharpness determines the "distortion" produced in a sustained note containing periodic constituents of several frequencies, and it is so used in telephone theory; but it does not exhibit conditions during the transient stage with which we are here concerned. The fact educed by Major Lee that "band width" $= 1/T$ is the same condition as $n\delta T = 2$ depends on his apparently arbitrary choice of 54 per cent of peak height at which to measure the "width." In my view the "band" method of telephony is inappropriate for investigating Morse reception. It is equivalent to disregarding the first term in the expression for q in the middle of page 193. As used by Major Lee, it leads to the conclusion that Fig. 6 is the Morse letter "1" "without appreciable distortion."

The use of two wave-lengths, either for mark and space, or for dot and dash, has been referred to by several speakers. I agree with Major Lee and Mr. Moullin in regarding it as an important method for reducing transients at the transmitter. Mr. Moullin proposes further to increase speed by utilizing the two wavelengths to permit the use of what would be practically siphon-recorder code with the space between dot and dash suppressed. The use of two marking wavelengths seems to me to be quite feasible, and the possible gain of speed without sacrifice of "shape" is considerable. A somewhat larger gain might, I think, be obtained from the analogue of a modified Gott form of Morse.* Marks would alternate in wave-length, the dash and dot would be of unequal length though of less than 3 : 1 ratio, and all spaces between marks would be suppressed.

Major Lee is, I think, mistaken in supposing that the receiver curbing which I propose renders the system more liable to attack from atmospherics. The use of curbing allows the receiver decrement for the reception of signals (and, of course, atmospherics) to be kept *lower* than it would otherwise be, and consequently confers some added protection. The higher the decrement at other times, e.g. after a mark has become effective and during spaces, the better.

Mr. Moullin's remarks as to the desirability, with regard to atmospherics, of keeping $n\delta T' < 2$, and his quantitative estimate of the effect of transmitter inertia (in the absence of two-wave signalling) are most interesting. The gain resulting from a reduced ratio between dash and dot, shown in his Fig. A, reopens the question of modification of the signalling code. I think that changes from the present ubiquitous transmitting practice are likely to come, but the significance which I have attached to $n\delta T$ will remain.

A relay having the properties named by Mr. Taylor might help in realizing good results from the curbed régime; but surely the feebleness of the holding-over force as compared with the moving-over force should be utilized by applying *larger* curbing damping, not applying it *earlier*. I think that Mr. Taylor is mistaken in supposing that curbing at the transmitter would reduce interference at other stations. It is a fact—paradoxical though it may seem at first sight—that the switching *off* of a transmitter can set up an interfering oscillation in a receiver which was not disturbed while the key was held down, and the greater the damping of the transmitter the stronger the interference would be.

I well remember trials of the Poulsen-Pedersen system of which Mr. Elwell speaks, and that, as he says, good tape was obtained at 200 words per minute. But the tape was photographic tape—which is much worse than siphon recorder slip, which is, again, worse than Wheatstone slip—and the value of $n\delta T$ was probably nearer 20 than 2. To attempt to cope with even English atmospherics and to moderate the transmitter power required, low decrements must be employed, and then the shaping considerations we have studied present themselves.

Like Major Lefroy, I was much struck by the close parallels between the ideas of acoustic damping pre-

* MALCOLM, *loc. cit.*, p. 350.

sented in Mr. Sutherland's remarks and those of the present paper. The problems of acoustic and wireless persistence are, of course, fundamentally alike.

I have no knowledge of the "ringing" observations mentioned by Prof. Fortescue, but I think that the phenomenon must now be well known to many experimenters, and at wave-lengths far below 15 000 m. Mr. Best has told us that he has taken actual decrement measurements in this condition at 4 350 m, and I have myself extensively observed and controlled the phenomenon while listening in Egypt to signals from Horsea at as low as 2 500 m. Smaller decrements than those making $n\delta T = 2$ for high-speed signalling could, I am sure, be obtained in practical work if wanted; but the answer given by the paper to Prof. Fortescue's question as to why a decrement of 0·0001 should be wanted, is that it never would be wanted except to bring $n\delta T$ down to a value such as 1 or 2.

PROCEEDINGS OF THE INSTITUITON.

703RD ORDINARY MEETING, 1 NOVEMBER, 1923.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 18th October, 1923, were taken as read and were confirmed and signed.

Messrs. J. O. Girdlestone and H. M. Sayers were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows:—

Elections.

Member.

Corns, Samuel William.

Associate Members.

Angus, James.
Bird, George Webber, B.Sc.(Eng.).
Evenden, Edward Frederick.
Hutton, Leslie Bertram, B.Eng.
Radbone, Victor James.
Reed, Frederick Raymond.
Villa, Charles Croswaithe.

Graduates.

Allcock, Harold John B.Sc.(Eng.).
Axon, Albert Edwin, B.E.
Burnett, Robert Ernest S. F.
Glover, Arthur Reginald.
Moiselle, Thomas Henry.
Musto, Romeo Jose.
Pollard, Thomas Royle.
Rennie, William.
Singh, Inder.
Thornton, Charles James.
Waglé, Vasant Krishna, B.Sc.(Eng.).
Woods, Ronald Forster.

Students.

Ahmed, Shaikh Muzaffar.
Aldridge, Stanley Walter.
Allan, James.
Arnott, Frank Reginald.
Bacon, Charles Edward.
Banks, Raymond Ernest.
Bartley, William Coppen.
Bingham, Walter Ronald.
Bintley, Bryan Noel.
Birch, Sidney.
Blackburn, Ernest.
Bourne, Percival Edwardes.
Brown, Kenneth Ivon.
Cawson, William Fox.

Students—continued.

Clare, Bernard Scott.
Cope, William Francis.
Crowe, Henry Eyre.
Davies, Harry Beaumont.
Davis, Percival Sydney.
Dean, John Alfred A.
Dean, William Henry.
Faulks, John Ruskin.
Fenwick, Raymond.
Gill, Benjamin Gerald.
Gregory, Herbert Turberville.
Greig, James.
Grubb, Edward Joseph, B.Sc.
Grundy, Geoffrey Earnshaw.
Heaton, Peter St. John.
Hemsley, Sydney Henrick.
Hitt, Donald George.
Horne, Thomas George.
Horner, Francis Henry.
Jollie, Andrew.
Jolly, William Joseph.
Jones, Cyril.
Jones, Harold Hosgood.
Jones, Lionel Adrian.
Kelly, Bruce.
Kibblewhite, Curtis.
Kipping, Norman Victor.
Kirkwood, Ian Ward A.
Knox, Alfred Harold.
McCarter, Alan Lailey.
McWhirter, Harry Roy S., B.Sc.(Eng.).
Macwhirter, Robert.
Mathur, Roshan Lal.
Meadmore, Claude Clement C.
Metcalf, Bernard Leslie, B.Sc.(Eng.).
Metcalfe, Percival Ignatius H.
Moffat, Frank Allan.
Moore, Cuthbert Grafton, B.Eng.
Murrell, Alfred Capper.
Nash, William Aitken.
Oldham, Charles Frederick.
Parker, Thomas Wilfrid.
Paynter, Rene Philip T.
Pearce, Claude Rieder.
Pearce, Owen Avis, B.Sc. (Eng.).
Perry, Walter William.
Pizzey, James Herbert.
Purnell, Percival Lawrence.
Rayner, Guy Stillingfleet.
Richards, Alfred Stanley.
Scanes, Ralph Boyce.
Shearley, Lewis Clifford.
Smyth, Cyril Jack.
Spratt, Hector Gordon M., B.Sc.(Eng.).
Stubbs, William Ronald.
Sutcliffe, Ronald Arthur H.
Taylor, David Bruce.
Taylor, Victor Arthur.
Teesdale, Eric Stanley.
Templar, Reginald George.
Thimbleby, Arthur Wilfrid.

Students—continued.

Thompson, Sydney Whitehead.
Thomson, Robert Batchen.
Torond, Leonard Bernonville.
Turner, Albert Edward.
Turton, George Thomas.
Vause, Dennis.
Vowler, John Creed G.
Watts, Basil Kingsford.
Wheeler, Edmund Frank.
Whitley, Ernest.
Woffenden, Arthur.

TRANSFERS.

Associate Member to Member.

Binns, Herbert Sugden.
McLeod, Neil Gloster.
Robinson, Bernard Augustus.
Robson, Robert Edward.

Graduate to Associate Member.

Aylott, Henry Joseph.
Combes, Frank Roy, B.E.
Furness, William John.
Jenkin, Ralph Meredith.
Purday, Allen Charlton.

Student to Associate Member.

Dance, Herbert Ernest.
Dobeson, Richard Gray, B.Sc.
Jones, Harold William, M.Eng.

Associate to Associate Member.

Clifford, Edgar Alan T. W.

Student to Graduate.

Bullen, Eric Harold S.
Cassal, Charles Victor.
Corbin, Cecil.
Gandhi, Khan Chand.
Murray, George Edgar W.
Patel, Kashibhai Bhikhabhai.
Vembu, N., M.A.

Graduate to Associate.

Burnham, Walter Witt.

The following list of donations was taken as read and the thanks of the meeting were accorded to the donors :—

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The President: I have to report the death of one of our Honorary Members, Maurice Leblanc. He was well known to every electrical engineer, and was at one time President of the International Electrotechnical Commission. As to his work, one may say almost that he invented the induction generator and the dampers used for the parallel running of alternators. The Council suggests that this telegram be sent to the Société Française des Électriciens: "The Institution of Electrical Engineers, London, send their deepest sympathy to all French engineers on the death of Maurice Leblanc, one of the most esteemed of their honorary members. When President of the International Electrotechnical Commission he won golden opinions from everyone. His achievements in engineering science have been of the greatest help to his brother electricians all over the world." I have also to report the death of one of our most eminent Members, Professor C. P. Steinmetz. His work is well known to you all, and it is suggested that we send the following cablegram to the American Institute of Electrical Engineers: "The Institution of Electrical Engineers, London, send their sincere condolences to their American confrères on the death of Charles Proteus Steinmetz, one of the early pioneers and one of the greatest exponents of the science of electrical engineering. His fame is world-wide; his work lives and will continue to live."

The proposed telegrams were unanimously approved, the members present standing in honour of the two deceased Members.

The President: I have now to announce that the Council have unanimously elected Colonel Crompton an Honorary Member. It will be unnecessary for me to dwell on the man or his career at any length. Born in 1845, he entered the Army in 1863 and served with his regiment in India. He was associated with Dr. Kapp in inventing the compound winding of dynamo-electric machines. That discovery goes right back to the

beginning of our profession. He has contributed many papers to the engineering Institutions; many of the expressions in these papers, such as "load factor," which have now become household words to the electrical engineer, were used by him in them for the first time. In a paper at the World Congress at St. Louis he pointed out the beneficial results of standardization, and as a result the International Electrotechnical Commission was formed. The late Lord Kelvin was its first chairman, and Colonel Crompton has been its Honorary Secretary for many years. He was our President in 1895 and again in 1908, the year of Lord Kelvin's death.

A paper by Mr. W. Wilson, B.E., M.Sc., Member, entitled "Industrial Research, with Special Reference to Electrical Engineering Development" (see page 61), was read and discussed, and on the motion of the President a hearty vote of thanks was passed to the author.

The meeting terminated at 7.50 p.m.

INSTITUTION NOTES.

Kelvin Medal.

The second triennial award of the Kelvin Medal has been made by the Award Committee to Professor Elihu Thomson, who is an Honorary Member of the Institution.

Associate Membership Examination, October 1923.

SUPPLEMENTARY LIST.

Passed.

Payne, L. S. (Wellington, New Zealand).

Associate Membership Examination, April 1924.

The next Examination will be held on the 3rd, 4th and 5th April, 1924. Candidates must be either Students or Graduates of the Institution, or have lodged with the Secretary a duly completed form "E" for election as Associate Member. Entry forms for the Examination, which must be completed and returned by the 1st March, and particulars regarding election to membership of the Institution may be had on application to the Secretary, The Institution of Electrical Engineers, Savoy-place, Victoria-embankment, W.C. 2. The Examination is being held this year about a fortnight earlier than in past years in order that those successful candidates who have qualified in other respects for Associate Membership may be elected before the end of the session.

Informal Meetings.

The following Informal Meetings have been held:—

44TH INFORMAL MEETING (5TH NOVEMBER, 1923).

Chairman: Dr. A. Russell (President).
Subject of Discussion: "Engineering Training" (introduced by Dr. A. Russell).
Speakers: Lieut.-Col. W. A. J. O'Meara, C.M.G., Mr. P. M. Baker, Professor C. L. Fortescue, Dr. R. M. Walmsley, Dr. F. T. Chapman, Mr. W. Day, Mr. A. W. Berry, Major T. Rich, and Mr. L. W. Phillips.

45TH INFORMAL MEETING (19TH NOVEMBER, 1923).

Chairman: Mr. J. R. Bedford.
Subject of Discussion: "Power in Telephone Exchanges" (introduced by Mr. A. B. Eason).
Speakers: Mr. F. Gill, Mr. P. Dunsheath, O.B.E., Mr. W. E. Rogers, Mr. F. Pooley, Mr. A. F. Harmer, Mr. A. G. Hilling, Mr. W. L. Wreford, Mr. W. Day, and Mr. J. W. Wheeler.

46TH INFORMAL MEETING (3RD DECEMBER, 1923).

Chairman: Mr. J. Coxon.
Subject of Discussion: "Electrical Apparatus for the Deaf" (introduced by Mr. C. M. R. Balbi).
Speakers: Dr. J. A. Fleming, F.R.S., Dr. Wm. Hill (St. Mary's Hospital), Mr. J. E. Kingsbury, Dr. S. Scott, Mr. M. D. Hart, Dr. F. Thompson, Mr. W. Day, Mr. F. S. Robertson, Mr. P. G. Pettifor, Mr. A. A. Williams, Mr. J. W. Wheeler, and Mr. L. V. Rein.

47TH INFORMAL MEETING (17TH DECEMBER, 1923).

Chairman: Mr. P. Dunsheath, O.B.E.
Subject of Discussion: "Students in Electricity Undertakings" (introduced by Mr. G. R. A. Murray).
Speakers: Captain J. M. Donaldson, Mr. A. F. Harmer, Mr. J. W. Thomas, Mr. G. W. Preston, Mr. E. F. Hetherington, Mr. W. E. Rogers, Mr. P. Dunsheath, O.B.E., and Mr. F. Pooley.

National Certificates and Diplomas in Electrical Engineering.

The following is a further list of colleges, schools, etc., which have been approved under the scheme drawn up by the Board of Education and the Institution [see *Institution Notes*, No. 39, page (18), July 1923].

Approved for Ordinary Grade Certificates (Senior Part-time Courses).

Birmingham Municipal Technical School.
Bradford Technical College.
Brighton Municipal Technical College.

Bristol—Merchant Venturers' Technical College.
Burnley Municipal College.
Coventry Muncipal Technical Institute.
Derby Technical College.
East Ham Technical College.
Erith Technical School.
Gillingham and Rochester Technical Institute.
Halifax Technical College.
Horwich Railway Mechanics Institute.
Liverpool Central Technical School.
London—Borough Polytechnic.
Plymouth and Devonport Municipal Technical Schools.
Poplar School of Navigation.
Preston—Harris Institute.
Salford Royal Technical College.
Smethwick Municipal Technical School.
Wolverhampton Municipal Science and Technical School.
Woolwich Polytechnic Institute.

Approved for Higher Grade Certificates (Advanced Part-time Courses).

Birmingham Municipal Technical School.
Bradford Technical College.
Brighton Municipal Technical College.
Erith Technical School.
Huddersfield Technical College.
London—The Polytechnic, Regent Street.
Poplar School of Navigation.
Preston—Harris Institute.
St. Helens Municipal Technical School.
Salford Royal Technical College.

Approved for Ordinary Grade Diplomas (Senior Full-time Courses).

Manchester College of Technology.
Portsmouth Municipal College.
Salford Royal Technical College.

Approved for Higher Grade Diplomas (Advanced Full-time Courses).

Brighton Municipal Technical School.
London—The Polytechnic, Regent Street.

The Benevolent Fund.

The following Donations and Annual Subscriptions were received during the period 1–25 January, 1924 (excluding those paid direct to the Institution bankers which will be published later) :—

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Wann, A. S. (Rugby)		8	6
Waring, J. (St. Helens)		2	6*
Warr, J. W. (St. Helens)		15	0
Warren, A. E. (London)		12	6
Warrington, A. R. V. (London)		5	0
Waterhouse, C. T. (Castleford, Yorks)		5	0
Watson, H. (Manchester)		5	0
Webb, R. (London)		10	0
Weston, C. B. (London)		3	6
White, A. E. (Warrington)		3	6
White, H. G. (Redhill)		5	0
Williams, E. J. (Inverness)		5	0
Womack, H. A. (Wokingham)		5	0
Wood, G. W. (London)		3	6
Wood, W. K. (Carlisle)		5	0
Woodhouse, W. B. (Leeds)	1	1	0*
Woodward, E. E. M. (Croydon)		5	0
Young, W. (London)		10	6

* Annual Subscriptions.

ELECTRIFICATION OF THE FRENCH MIDI RAILWAY.

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SUMMARY.

After a brief description of the experiments made before the war on the Midi Railway in the way of electric traction, the author gives an account of the extensive electrification work now pursued by that Company in accordance with the new standard regulations of the French Government, and of the first results already obtained on the electrified lines.

The Midi Railway of France extends in the southernmost part of that country from the Atlantic Ocean to the Mediterranean—from Biarritz to Perpignan—along the snow-covered Pyrenees, sending off branch lines up most of the valleys of that chain of mountains. It also runs up north of Beziers across the Cévennes district, a very wild, picturesque and mountainous country.

On account of these features, several of its lines have very steep gradients; grades over 3 per cent are not infrequent. The difficulties encountered in the working of such lines with steam locomotives, as well as the fact that water power is close at hand, were bound to place the problem of electric traction very early before the Midi Company.

It began effectively in 1902, when the company undertook the construction of a narrow-gauge line, 35 miles long, from Villefranche-de-Conflent to Bourg-Madame in the eastern Pyrenees, a single-track line climbing to an altitude of 5 000 feet, with long 6 per cent grades and curves of 200 ft. radius. Electric traction was decided upon, and the chosen system was direct current, third rail, at 850 volts. That was at the time the highest d.c. voltage used in Europe for traction.

The motor-cars (either freight or passenger), with a certain number of trailers composing the trains, were fitted with the Sprague multiple-unit control.

The line was opened in 1910 and has since worked to the entire satisfaction of the company, carrying a relatively heavy traffic to which the construction of the great mountain resort of Font-Romeu has substantially contributed.

When the line was built, it was considered an optimistic view to expect an annual return of 5 000 francs per mile. It is actually 40 000 francs, although the fares have been increased only from 100 to 150 per cent.

In the meantime, the company had been led to consider electrification of lines of normal gauge in connection with proposals for new railways in the Pyrenees; among these, two lines, crossing directly through the chain into Spain, involved, besides tunnels several miles long, gradients of over 4 per cent.

At this time—namely, between 1908 and 1910—the single-phase system had made sufficient progress to be considered as practically reliable, and the use of overhead construction and a high voltage seemed to secure the most economical installations.

In order to verify this through extensive tests, the company equipped 15 miles of line between Ille and Villefranche-de-Conflent. Six different systems of overhead construction—all based on the catenary principle—were effectively applied on this section.

The type of current was single-phase, 16 cycles, 12 000 volts on the contact wire.

Six locomotives, built by different constructors according to the company's requirements, were submitted to a series of tests, and three of them, having successfully passed such tests, were accepted.

It was accordingly decided to equip with the single-phase system 70 miles of double track between Pau and Montréjeau, and the single-track branch lines of Pierrefitte, Bagnères-de-Bigorre, Arreau and Luchon, measuring 63 miles. For this purpose a power house equipped with six 2 500-kW generators was built at Soulom. Orders were also placed for 30 motor-cars, each of 500 horse-power, and for 24 new locomotives.

The tests revealed serious trouble in the telegraph and telephone lines along the track, due to inductive interference by the single-phase traction current.

This question was closely investigated by the Midi Company, and a solution was found which consisted in running two extra wires beside the trolley wire, namely:

(1) A negative feeder along which the return current is forced by means of booster transformers, instead of going back through the track rails.

(2) A counter-voltage wire in which there is an alternating voltage directly opposed to that in the trolley wire.

By these means, compensation was obtained for both electromagnetic and static induction. The whole line between Perpignan and Villefranche, 30 miles long, only fed at one end, is actually worked with single-phase current without any trouble on the telegraphs and telephones.

The outbreak of war brought these experiments to a standstill. The whole of the energy available from the existing power houses, as well as from a new 25 000-kW plant equipped at Eget during the war, was given over to munition work, and it was only after the armistice that the company could resume work in the matter of electrification. In the meantime, however, things, from a technical point of view, had taken a new turn.

The French Government had decided to standardize for electric railways both the primary current and the traction current, in order that different power plants could work in parallel and that locomotives could be used indiscriminately on all the electrified lines.

A Commission was appointed at the end of 1918 by the Ministry of Transport, to decide on one system to be accepted by the French companies.

In 1920 this Commission, after close investigation of the different systems in use in France and abroad, produced its conclusions, which were adopted by the Government.

The primary current is to be three-phase, 50 cycles. The standard type of traction current is to be direct current at 1 500 volts, with the proviso that, in exceptional cases, 3 000 volts can be used.

Either overhead or third-rail equipments are permitted, and locomotives are to be fitted with current-collecting apparatus suited to both.

The reasons for this choice were the following:

Three-phase 50-cycle current is already standard in France for distribution systems, and it was deemed advisable to adopt the same type for the power plants built by railway companies, in order to facilitate interconnection and mutual help, the result being not only greater security, but also better utilization of both the power plants and transmission lines.

The type of primary current being thus fixed, the single-phase system loses one of its chief advantages, which is to do away with rotating machines in substations when low-periodicity current for traction can be directly produced at the power house. The necessity for substations fitted with motor-generator sets for the production of single-phase current would have involved high expense and low efficiency, whereas the use of rotary converters for producing direct current allowed much more favourable conditions.

On the other hand, the use of direct current was considered to be the best means of overcoming inductive interference on low-tension conductors.

Other advantages were also considered, such as lower weight and cost of direct-current locomotives, greater overload capacity, and cheaper maintenance of their motors.

As to the voltage for traction lines, 1 500 volts was chosen as being the maximum voltage allowing the use of a third rail, which certain companies wished to keep, notwithstanding the advantages which a somewhat higher voltage might have procured.

These decisions implied for the Midi Company the abandonment of the larger part of the work already done. Power plants, transmission lines, substations, overhead equipment and locomotives had to be fundamentally modified for use with the direct-current system.

The company set to work immediately on these alterations as well as on a new programme of electrification.

In two years' time, the first results have been attained by the appearance on the Pau–Tarbes division, in the last months of 1922, of the first French 1 500-volt direct-current locomotives.

The electrification work is actually carried out in the western part of the Midi system. The Toulouse–Dax line is to be entirely equipped this year, and is already partly run by electricity. Its branch lines are being changed over from single-phase to direct current.

The equipment of the main line from Bordeaux to Hendaye has been begun, as also of its branch lines to Arcachon and Biarritz. Other lines will follow both in the Pyrenees and the Cévennes districts, the whole length of road to be electrified in the next 10 years being nearly 2 000 miles.

Current is actually produced in the two hydro-electric stations at Soulom and Eget, the first equipped with 21 000 and the second with 35 000 horse-power, this last from a fall 2 300 feet high.

In addition to this, the Midi Company is building on the Gave d'Ossau three new power stations equipped for 130 000 horse-power with falls ranging from 600 to 2 500 feet. Other power plants are designed in the central and eastern Pyrenees for the time when electrification reaches those districts.

The current produced by all these plants is three-phase, 50 cycles, at 60 000 volts. It is transmitted by feeders following the railway, and in addition part of it is transformed to 150 000 volts for long-distance transmission. Lines for this purpose are already constructed as far as Bordeaux and Toulouse. Their total length is actually 420 miles, and the longest distance between step-up and step-down transformers is 175 miles.

These lines have been given a larger capacity than required by the needs of the railway. They are, in fact, meant to transmit, not only for traction, but also for distribution purposes, energy produced by numerous power plants all working in parallel. This transmission over lines belonging to the railway will be subject to taxes which will cover part of the expense.

Each line, designed to carry from 30 000 to 50 000 kW, consists of three copper cables each of 283 000 circular mils (0·222 square inch) section. A steel earth wire is provided for protection.

The cables are suspended by insulator chains of 9 plate-type elements from steel towers 66 feet high and normally 660 feet apart. Two of these lines, entirely independent of each other, join the Pyrenees to Bordeaux.

Transformation from 60 000 to 150 000 volts, and vice versa, is carried out in two step-up stations, equipped for 60 000 kW, and in three step-down stations equipped for 80 000 kW. The latter are provided with synchronous condensers of 60 000 kVA total capacity. All these stations are of the outdoor type.

Energy for traction is distributed along the railway by 60 000-volt feeders issuing either directly from the power plants or from the transformer stations. They are generally fixed to the same supports as the contact line. They consist of three 200 000 circular mil (0·157 square inch) copper cables or aluminium equivalents.

Substations for converting three-phase current into direct current are built at distances varying from 8 to 20 miles, the drop in the line voltage not exceeding 20 per cent under normal service.

Different types of converting apparatus have been used. Besides the classical groups of two 750-volt rotary converters connected in series, some substations have 1 500-volt 750-kW rotary converters as single

units. These are, the author believes, the first machines of this type wound for 50 cycles and they have been entirely successful. They can withstand 200 per cent overload during 5 minutes, without flashing over.

The newest feature, however, is the use, in some substations, of mercury rectifiers producing 1 500-volt direct current. Five substations have been equipped in this way, containing, in all, 16 groups each of 1 200 kW. Each group consists of a pair of cylinders connected in parallel, and fed with 12-phase current produced by special transformers.

The efficiency of these machines is very high, and practically independent of the load. Their overload capacity is equal to that of the rotary converters. Being static machines, they require very little attendance. We have so far experienced no difficulty in keeping the vacuum in the cylinders. The current they generate, although slightly undulating, is well withstood by the traction motors.

All substations possess high-speed circuit breakers on each group. In most of them, such high-tension apparatus as transformers and oil switches is placed out of doors.

The line equipment is of the double-catenary type. It consists of a steel messenger cable, an auxiliary messenger, and a contact wire, the last-mentioned being made of grooved copper of 0·155 square inch (100 mm^2) cross-section. The auxiliary messenger is suspended from the main messenger by flat steel hangers 30 feet apart on the straight and 15 feet apart on curves. The contact wire is fixed to the auxiliary messenger by clamps maintaining the two wires in a vertical plane.

On curves the catenary system is similar to that adopted on the Pennsylvania Railway. The line has no pull-offs, and follows the same curve as the track, the hangers taking an inclined position. This disposition gives a very smooth and uniform contact, and has the advantage of being self-compensating when the temperature varies.

On straight sections, pull-offs are generally used on the auxiliary messenger. Elastic pull-offs, consisting of two helical springs disposed V-wise, have been applied with success. On some sections, however, we have, as an experiment, suppressed the pull-offs. In this case the line is designed as a succession of curves staggered alternately 10 inches on either side of the middle of the track, and its tension is sufficient to prevent swinging. Up to now, this seems to give satisfaction.

The distance between supports varies from 300 feet on straight sections to 150 feet on curves under 2 600 ft. radius.

Different kinds of supports have been tried. On single track, the bracket type is generally used. We have also types of bracket construction for double track, with either steel or concrete poles. The last type adopted for double track is a cross-span construction consisting of two steel I beams assembled in the shape of a pointed arch. On these supports are fixed the 60 000-volt three-phase distribution line, the 1 500-volt direct-current feeders and catenary line, and in addition, in some cases, a 10 000-volt three-phase line for auxiliary and signal service.

Chain insulators are used for the high-tension line, as far as is allowed by clearance considerations. For the direct-current lines, double insulation is the rule, by means of either rigid or suspended insulators, the latter type being preferred.

Protection of transmission and contact lines against excess of current or voltage has been especially cared for. The high-tension lines are protected by selective relays and oil switches so disposed as to cut out automatically any section on which a breakdown occurs. The system is, moreover, earthed at one of the power houses at the neutral point of a transformer. It is protected against pressure-rises by earthed reactance coils with iron cores, and against steep-front surges by Capart apparatus consisting of mica condensers branched between two inductive coils, one of which is shunted by a resistance.

Direct-current machines in the substations are protected, in addition to the oil switches and quick-acting circuit breakers, by inductive coils and by an earthing device composed of a condenser shunted by a resistance.

Track bonding has been the object of a long discussion on the part of the Midi Company. We have experimented with a great many different types of bonds, and it must be said that up to now none have proved entirely satisfactory. The best, to our mind, consists of a pair of short copper bonds, made either of cable or packed strips, connecting each end of the fishplate with the corresponding rail. The fixing is obtained by through bolts or by split steel rings forced into the rail holes.

The different lines to be electrified present very diverse features, including level main lines carrying fast passenger and heavy goods trains, branch lines to watering places where traffic assumes a partly suburban character, and mountain lines with exceedingly steep grades requiring very powerful locomotives. Nevertheless, we have succeeded in limiting the number of different types of locomotives to four. These types have been studied jointly by the company's officials and by the makers, namely, the Société des Constructions Electriques de France, which is associated with the English Electric Company.

The first electrical equipments were made in this last-mentioned company's works at Preston, and the succeeding ones in the Lyons works of the Société des Constructions Electriques de France.

The locomotives are constructed in extensive shops especially built by the latter at Tarbes, in the middle of our electrified system.

The first two types of engines are a passenger and a freight locomotive similar to one another except for the gear ratio. They are mounted on two 4-wheel motor trucks. Each of the four axles is driven by a geared, nose-suspended motor.

These motors, of Dick-Kerr design, with 4 poles and commutating poles, are wound for 1 500 volts. Under forced ventilation, their one-hour rating is 350 and their continuous rating 250 horse-power. The total weight of the locomotive is 72 tons; and the speed limits are 55 miles per hour for the passenger engine and 40 for the freight engine. The motor control is the

Dick-Kerr cam-shaft multiple-unit system. Different speeds are obtained through series-parallel and field-shunting combinations.

Low-tension current for auxiliary service is produced by a 72-kW group. This includes, mounted on the same shaft, a 1 500-volt motor, two direct-current generators and two fans for ventilating the traction motors. One of the generators produces 120-volt current for the control circuits, for lighting the train and for feeding the air compressor. The second one is a variable-pressure dynamo used for exciting the motor fields when regenerative braking is in action.

Owing to this arrangement the locomotive has but one auxiliary 1 500-volt motor, which is an advantage, this being, as is well known, the delicate part of high-tension direct-current equipments.

The coupling devices and buffers are fixed to the truck frames, and these are themselves coupled together by a double drawbar and lateral buffers, so that the tractive effort is not in any way transmitted by the centre pins.

The cab suspension is so designed as to leave the highest degree of freedom to the trucks. The contact surface between centre plate and pivot has its concavity turned downwards and its centre near the axle plane; this eliminates reactions when the bogie pitches in any direction. To prevent the cab tilting, lateral springs suspended by swinging rods are interposed between the cab and the truck frames. This device is preferable to the ordinary support blocks, in that it allows perfectly free horizontal displacement. No equalization of the truck suspension has been found necessary.

Each motor drives its axle by two symmetrical gears. In order to avoid axle breaking, which has given a great deal of trouble on our first electrified lines, each gear-wheel, instead of being mounted on the axle, consists of a cogged rim bolted on to the truck wheel-centre.

The locomotive is equipped with both the Westinghouse automatic air brake and a straight air brake. Compressed air is provided by a Westinghouse gearless air compressor. In addition to these, an electric brake is provided. For the first machines, this is based on the regenerative principle, the current generated by the motors being sent into the trolley line. In this case the motors are separately excited by an auxiliary generator, and speed regulation is obtained by varying this generator's excitation.

Experience has shown that the saving of energy resulting from regenerative braking is comparatively small, and does not justify the complication it introduces into the locomotive's equipment. It has therefore been abandoned for the future, and rheostatic braking adopted in its place.

Whatever the system, electric braking is to be used for going down long grades, so as to save the wear of brake shoes. It is accordingly designed so as to hold the load which the engine is able to haul up the same gradient.

The current-collecting apparatus has been designed with special care, in order to obtain a smooth contact and to avoid sparking. It consists of a pantagraph fitted with ball bearings at each joint. The collector is made of two steel pans lined with copper strips and borne on helical springs. By these means, the greatest flexibility has been realized and good collection obtained at all speeds.

Passenger trains are lighted and heated by current obtained from the engine through special couplers. The lighting current at 120 volts is taken from the machine's auxiliary group.

Heating is provided by 1 500-volt current from the line. This current is sent into special radiators placed under the seats in the car compartments and protected by steel tubes and perforated steel plates. The heating couplers between cars are so designed as to prevent dangerous arcing while uncoupling. To secure this, an auxiliary wire fed with low-tension current runs throughout the whole length of the train. Its couplers are mechanically interlocked with the heating couplers, so that the latter cannot be uncoupled unless the former have been previously uncoupled, which automatically results in the opening of the main switch controlling the heating circuit on the locomotive.

A series of 90 of these machines is under construction, 13 of which are already running.

The freight locomotive is to haul trains up to 1 800 tons on the level. On mountain lines, this same engine can haul a 185-ton train on a 4 per cent grade. A helping engine at the rear will be normally used on these lines.

Another type of machine is a motor-car for suburban and branch-line services. It is carried on two 4-wheel bogies of the swinging bolster type. Each of the four axles is driven by a series nose-suspended geared motor. These motors are wound for 750 volts and connected two in series. They are self-cooling. The continuous rating of each is 125 h.p., and the one-hour rating 175 h.p. The maximum speed is 50 miles an hour.

Each axle has only one gear, similar in construction to those on the locomotives. The tractive effort is transmitted from the truck frame to the swinging bolster through articulated drawbars instead of the ordinary friction plates, which wear out quickly and impair the bolster's lateral displacement. The motor control is the same as on the locomotives. Air and hand brakes and electric rheostatic braking are provided.

The car is entirely of steel. It includes a third-class compartment with central aisle and reversible seats, a luggage compartment and two drivers' platforms. The total weight of the vehicle is about 52 tons and the number of seats is 48, besides which 32 standing passengers can be accommodated.

Those three types of machines are sufficient to haul any kind of train either on mountain or level lines, up to 50 miles per hour; but for higher speeds a special type of express locomotive had to be designed.

This problem is still under consideration in many countries, and could scarcely be said to have found an entirely satisfactory solution up to now.

The trouble, which is more of a mechanical than of an electrical character, consists mainly in the transmission between motor and driving axle. In the case of an express locomotive, the ordinary gear transmission requires a high peripheral speed for the pinions, at which their lubrication becomes very difficult. This difficulty disappears in the gearless type of locomotive

where the motor armature is fixed directly on the driving axle; but then the unsprung load increases to such a point as to tell severely on the track. To lighten this, the motors are often set in the cab and connected to the axles by means of driving rods. But this construction generally results at high speed in abnormal vibrations of the machine and in stresses leading to breakage of rods, cranks and even of the engine frame.

In order to avoid these various difficulties, the Midi Company has kept, for its high-speed locomotive, to the geared type, but with entirely suspended motors and quill drive. The particular feature is the use of a conical gear which allows smaller pinions and a lower peripheral speed and, moreover, is easier to lubricate than a straight gear.

Two locomotives previously built for use with single-phase traction were transformed according to this programme by the Société des Constructions Electriques de France. The general disposition of these machines is 4—6—4, that is, three driving axles independent of each other, and a 4-wheel bogie at each end.

The driving wheels are 69 inches in diameter. The adhesive weight is 54 tons, and the total weight 102 tons. The bogies are elastically centred and are practically identical with steam engine bogies.

The equipment of each driving axle is composed of a pair of vertical motors placed inside the cab and fixed to the main frame. The two pinions drive a double-cone gear-wheel fixed on the middle of the quill, and this in turn acts on the driving wheels through an elastic transmission.

The motor shafts are suspended on ball bearings at their upper extremity. At the lower end, the whole gear is immersed in oil. A pump raises the oil to a tank at the top of each motor, whence it flows down through ducts bored in the motor shaft.

The six motors are wound for 500 volts and are connected three in series. They are 4-pole motors (2 active and 2 consequent poles) with commutating poles. The one-hour rating of each is 375 h.p., that is, 2 250 h.p. for the whole machine. These motors, of very peculiar construction, have been designed and built at Liége, in the works of the Société des Constructions Electriques de Belgique, another firm associated with the Constructions Electriques de France.

The motor control is of the same type as in the former machines, and the maximum speed is 75 miles per hour. No electric braking has been provided for these machines, which are only for level lines. They are fitted with the Westinghouse automatic and straight air brakes.

The current-collecting apparatus consists of three pantagraphs similar to those previously described, each of which can collect, without sparking, 800 amperes at the maximum speed.

The machine has been tested up to a speed of 78 miles per hour, keeping perfectly steady on the track, without any nosing. This will perhaps be a surprise to those who believe that a locomotive with a symmetrical wheel-base cannot run smoothly at very high speeds. It may be of interest, therefore, to look into the matter more closely and to ascertain the origin of this somewhat legendary belief.

The above opinion was expressed by the Pennsylvania Railway officials, at the conclusion of tests carried out in 1907. These tests included the following machines :—

(1) Several steam locomotives, either American or Atlantic type.
(2) An electric locomotive with two driving axles rigidly connected to the frame and a 4-wheel leading truck (a disposition quite similar to that of an American type steam locomotive).
(3) Several electric locomotives with two 4-wheel trucks.

In fact, the symmetrical engines were limited to this last type, which behaved fairly badly at express speeds. Whilst, however, this inferiority was too hastily attributed to symmetrical construction, its real cause, to my mind, was quite different: first, the lack of a rigid wheel-base owing to which a 2-truck machine has a tendency to sway at high speeds; second, the rigid fixing of the pivots on the truck frames through which the side blows are transmitted from the track directly to the main frame; third, a centre of gravity decidedly lower than that of the steam engines.

The verdict thus delivered against symmetrical engines cannot, therefore, be considered to be final. Several engines—either electric or steam—which show perfectly symmetrical wheel arrangements, and ride nevertheless without difficulty at a fairly good speed, have before now brought it under suspicion; and the author will venture to say that the Midi Company's express locomotive has given it the final blow.

It will be noticed that this machine has been so designed as to avoid precisely the three defects which have just been pointed out. It has a rigid wheel-base 13 feet long, which keeps it steady on the track. The trucks are elastically centred through side springs; and, owing to the raised motors, which are set inside the cab, the height of the centre of gravity is similar to that on a steam engine.

This type has been adopted for a series of express machines to be built for level lines; but a new and more powerful machine of similar construction with four driving axles and a normal rating of 3 200 h.p. is already under consideration. It will pull on the level a 600-ton train at 60 miles an hour, or a 380-ton train at 70 miles.

It may now be asked what results, either economical or technical, the Midi Company has already obtained or expects to obtain through electrification of its lines.

Although electric traction is already in use on 140 miles of our lines, it is still too early for us to give figures as to its cost, as only 37 miles are established under standard conditions, whilst several hundreds of miles are under construction. Nevertheless, we may say that in many ways electrification has so far proved profitable.

Not only do drivers of electric locomotives get lower wages than steam locomotive engineers, but also their daily run is 30 per cent longer, on account of less time being spent for engine-shed operations.

As to the machines themselves, worked by several drivers they cover daily about 2·5 times the distance covered by a steam engine, which more than compensates for their higher price.

The cost of hydro-electric energy is naturally much less than that of the coal it saves.

Important economies are also realized on engine-shed and repair-shop expenses. Electric locomotives require much less labour for their maintenance than steam locomotives, a great many daily operations, such as coal and cinder handling, water pumping, tube blowing, boiler washing, etc., being entirely eliminated, whereas repairs are greatly simplified through the suppression of the boiler and much mechanism.

On the whole, and in spite of most of our electrification work having been done under very unfavourable price conditions, we have every reason to be confident that the operation will prove profitable.

A strong support to this belief is the rapid increase in traffic and revenue on our electrified lines, consequent on faster and more frequent trains. As a matter of fact, the technical advantages of electric traction are still more certain than the economical ones.

It allows, especially on mountain lines, a higher commercial speed. For instance, on our main line from Bayonne to Toulouse there is a grade of 1 in 30, $7\frac{1}{2}$ miles long, which takes an express hauled by a steam locomotive 34 minutes to climb. The same train hauled by an electric machine gets to the top in 13 minutes.

On the Transpyrenean lines long grades of 4 per cent will be ascended by passenger trains at a speed of 25 miles an hour, whereas it is doubtful whether steam engines could work any effective service on such a line.

Even on level lines train schedules can be made quicker, on account of a more regular and uniform speed being maintained by the electric locomotive, and of the suppression of those stops which are necessary only for taking in water. On the Bordeaux-Hendaye line, where the maximum grade is 1 in 200, our fastest train, the Southern Express, actually covers the 92 miles from Bordeaux to Dax in 1 hour and 49 minutes. With an electric locomotive it will run at an average speed of 65 miles, and gain about 25 minutes on the present schedule.

Trains can also be made more frequent without prohibitive cost. During the war, when the strictest economy prevailed and the daily number of trains was reduced, on a great many of our lines, to two in each direction, we could always maintain without extra expense four or five trains in each direction on the electrified lines. Our present programme is to establish around our mountain or seaside resorts a service of light and frequent trains very similar to a suburban service, and this can only be accomplished by electric traction.

It is perhaps needless to say that, from the traveller's point of view, the suppression of smoke and cinders is also a great improvement. This is particularly the case with lines such as the Transpyrenean running through tunnels several miles long.

Electric traction will also prevent the costly forest fires which are started too often by locomotive sparks in the forest properties along the railway.

One of the greatest advantages, however, to be found in railway electrification as carried out in France is the construction of a close network of electric transmission lines. In our country, extensive areas are mostly agricultural and only to a small extent industrial. In such districts the demand for electrical energy could scarcely be sufficient to justify the high expense involved in long transmission lines. On the other hand, a great many railway lines, on account of limited traffic, require only a small proportion of the current which the high-tension wires can carry, and this condition in general corresponds to cases where electrification could not be economical. In many cases the combination of these two unprofitable operations makes a profitable one, and the result will be not only to improve railway service considerably, but also to bring cheap electric current to every town and to a large number of small localities. While our 150 000-volt main transmission lines supply large centres such as Bordeaux and Toulouse, the 60 000-volt wires that follow the railway everywhere and feed step-down transformers in substations spaced some 15 miles apart will leave but little to do in order to build distribution systems covering the whole country.

When this is done on the 2 000 miles of road that the Midi Company intends to electrify, also when the Paris–Lyons–Mediterranean and Paris–Orleans companies have on their side electrified some 3 800 miles in accordance with a similar plan, and when the latter company has constructed the 300-mile 150 000-volt line from the Dordogne power plants to Paris, then not only railway electrification, but also public and industrial electrification, will have made a decided advance in France.

Discussion at the Joint Meetings of The Institution and the Société des Ingénieurs Civils de France (British Section), 22 November, 1923, and 10 January, 1924.

(22 *November*, 1923.)

Lieut.-Colonel H. E. O'Brien: I feel that what has been done in France in regard to standardization should be an example to us in this country: at the present moment, the standardization of the voltage and the various appliances in connection with electric traction in this country is little more than the pious expression of a wish on the part of a group of individuals who formed a Committee some time ago. On the other hand, both the French Government and the French electrical industry appear to have grasped the problem boldly and to have come to a very definite decision as to what they are going to do in the way of standardizing the voltage and the system generally for electric traction all over the country. It is particularly noteworthy that the Midi Railway, which had expended a very large sum on single-phase electrification, was, for the good of the country, ready to abandon the whole of that work and to fall in with the standardization which had been decided upon for the rest of the country. Although the electrification of main lines has a very definite though possibly limited scope in this country, yet that scope has as yet been but very dimly appreciated by railway managements here. The Englishman is intensely conservative; he is very slow to take up

anything new. When Mr. Garbe brought out superheating for locomotives and invited the locomotive engineers of this country to inspect what had been done in the way of coal and water economy by superheating, only two of our engineers responded to his invitation; the rest disregarded it, with the result that this country was one of the last to take up locomotive superheating. The varying apparatus which has been used in substations in the shape of direct 1 500-volt rotary converters and mercury-arc rectifiers will be of great interest when we can hear more about their actual performance, the mercury-arc rectifiers particularly. It is especially interesting, from a railway point of view, to learn that it has been possible to deal with such varying traffic on such widely different gradients with so few types of locomotives. Such a result can only have been attained by a great deal of work and co-operation between the manufacturers and the users. It is also rather striking, to railway people at any rate, to consider the features of these electric locomotives. The freight locomotive, which weighs 72 tons and has a one-hour rating of 1 400 h.p., may be compared with a steam locomotive which would weigh 120 tons and would only have a rated continuous drawbar horse-power of about 1 200 when in first-class condition and provided with picked fuel. Perhaps the most interesting part of the paper, apart from the wealth of technical detail in it, is the statement at the end to the effect that the technical advantages of electric traction are still more certain than the economical ones. I hope the author will, in the course of a very short time, be able to tell us that the economical advantages are even more certain than the technical ones, because there seems to be no uncertainty about the possibility of the solution of technical problems, whereas the economic problems are much more difficult. The people whom we engineers have to convince are the financiers. Therefore it is of great importance that actual figures should be brought forward showing what these economies are. The author, however, indicates very clearly that great economies will be effected in dealing with the locomotive as a machine. It is probable that in a very short time we shall have no difficulty in showing that the electric locomotive as a tractor on the railway is a very much more economical machine than any steam locomotive that can at present be built or is ever likely to be built. The whole problem will resolve itself into a question of the cost at which the current can be supplied to the locomotive. The author is in a slightly different position from engineers in this country in that he has water power at his disposal and the cost of energy will tend to become very much less the more he uses, whereas with us the cost of energy will not diminish in the same ratio.

Mr. E. M. Malek: The question resolves itself into one of economics. Technically I think that it is solved or is capable of solution. The French first of all determined to standardize and to scrap all lines hitherto in operation which did not lend themselves to modification. They looked upon the distribution of energy from every point of view and did not regard the electrification of railways as something apart and needing the supply of electricity for this particular purpose in isolated portions of their territory. I am certain that there is no other way of dealing with the problem than by looking upon it as a whole, the railways being the biggest potential users of energy and their systems the most convenient route for general power distribution. The Midi and other companies having laid down a programme which gives the French manufacturers a period of 10 years in which to look ahead, the latter have been able to organize production. This is very different from building special machines in small numbers, as development costs are wiped out and much money is saved in other ways. Colonel O'Brien has pointed out the difficulty—also mentioned by the author—of proving the direct financial benefit derived from electrification. We have to consider the capital expenditure. French engineers are noted for being able to design structural steelwork with less weight of material and at a lower cost of manufacture than almost anyone else. If the author's invitation is accepted, a tremendous impression will be created by the efficiency and cheapness of the overhead structures, whether for primary or for secondary distribution. I hope with Col. O'Brien that the author will give us, at a later date, some particulars of the economic results obtained.

Lieut.-Col. F. A. C. Leigh: On page 213 the method adopted to prevent inductive interference with the communication circuits in the case of the single-phase lines is very interesting, but I should like to know whether the present system costs less than that adopted on the Swiss railways. In view of the adoption of the overhead collector system by the Midi Company, why has the voltage of 1 500 still been retained? Presumably the pressure was decided upon because of the difficulties inherent to the third-rail system. The author mentions that 60 000-volt transmission wires are run on the same structures as the track overhead construction. It would be interesting to know whether there have been any difficulties with the communication circuits due to this, and what precautionary measures, if any, have been taken to avoid interference. On page 215 the author refers to the undulations in the voltage due to the use of the mercury-arc rectifiers. Have these undulations any effect on the telegraphic and telephonic communications? On the same page also the author rather indicates that he prefers a short bond for the third-rail system. On the old North-Western system our experience has been rather the reverse; we find that the long bond is more effective. On page 216 the author mentions that the auxiliary circuits on the locomotive are dependent upon one 1 500-volt motor only. If this is so, it would appear that, unless there are other special arrangements, the locomotive would be out of action if anything happened to this motor. The design referred to on page 217 is unique, and it will be interesting to learn whether satisfactory results are obtained from that system after it has been in use for some time. I should like to know whether the French engineers would have embarked upon the undertaking had not natural resources in the shape of water power been available. In North Wales there is

some water power, and certain inquiries have been made as to the power available there. Information has been obtained that under the proposed immediate development of this water power something like 350 million units a year could be produced. I should be glad if the author would state how many million units a year are available in France from water-power resources. I presume we may take it that all the power referred to in the paper will not be used at the moment for the railway only, but also for the encouragement of industrial enterprise. Has the Midi Railway been granted powers to distribute electricity for industrial purposes, like the power companies in this country, and if so is it controlled as regards the prices that it may charge?

Mr. T. Stevens: I have had four opportunities within the past six months of seeing parts of the work on the Midi Railway, and particularly of noticing the considerable progress made during that time. I greatly appreciate the action of French engineers in definitely limiting the voltage allowable on a third rail. In the "Final Report of the Electrification of Railways Advisory Committee of the Ministry of Transport" the pressure is given as 1 500 volts and multiples of that voltage. We have, however, to go to the technical Press to find what the limit is. In the *Tramway and Railway World* my statement was quoted: "It seems extraordinary that the Committee agreed to a multiple of 1 500 volts on third rail without even wisely limiting the multiple." An editorial comment on that read: "We consider where multiples of 1 500 volts were named in the Advisory Committee's report that no member of that Committee had any intention that it should be located near the ground." The present paper definitely states that 1 500 volts was chosen as being the maximum voltage for France allowing the use of a third rail. I consider that that pressure is satisfactory so far as the safety of the public and of the workmen on the lines is concerned. The author states that a steel earth wire is provided for protection. We all include steel earth wires in our estimates, but I should like to ask the author if he has made any

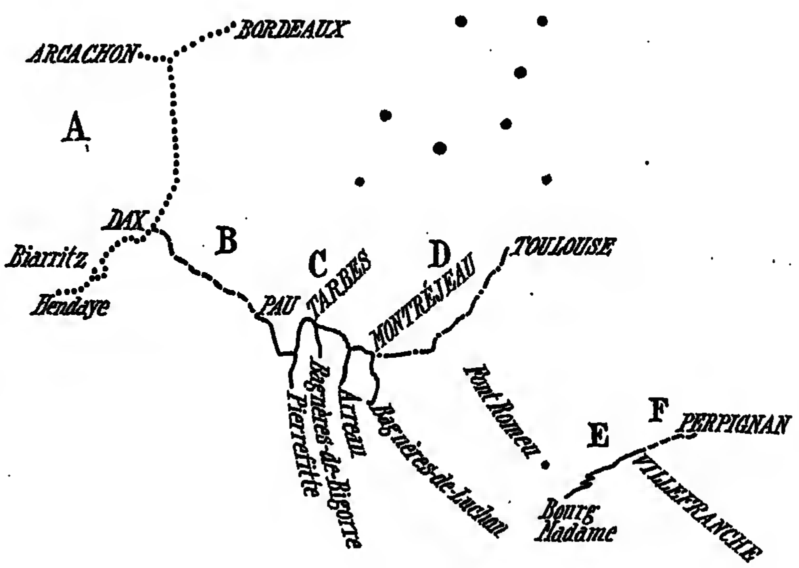


FIG. A.

definite experiments or has any definite experience to prove that it really does give protection. The voltage-drop on the line, with distances of between 8 and 20 miles between substations, is given as 20 per cent. Does that figure include the whole circuit? Calculations that I have made on published figures of the Chicago, Milwaukee and St. Paul Railway, show, with an annual saving of 20 per cent on the capital cost of electrification, that under normal conditions there is

TABLE A.

*Through Passenger Trains (Omitting Local and Goods Trains).**

Ref. to sections in Fig. A	A	B	C	D	E	F
Route	Bordeaux–Hendaye	Dax–Pau	Pau–Montréjeau	Montréjeau–Toulouse	Bourg-Mad'e–Villefranche	V'franche-Ille-Perpignan
Distance in miles ..	145	52	70	65	32	29
No. of through passenger trains per day	*Up* 9 *Down* 9	*Up* 7 *Down* 8	*Up* 4 *Down* 5	*Up* 7 *Down* 7	*Up* 5 *Down* 5	*Up* 6 *Down* 6
Schedule speeds (including stops):	*Up* *Down*	*Up* *Down*	*Up* *Down*	*Up* *Down*	*Up* *Down*	*Up* *Down*
Fastest trains, m.p.h.	36 41	42 40	25 24	40 36	15 15	15 14
Slowest trains, m.p.h.	18 18	21 22	17 18	23 21	13 15	12 10
No. of stops	9 to 16	2	7 or 8	4 or 5	6	3
Average run, miles ..	16 to 9	26	10 or 9	16 or 13	6	6
Electric traction put into service ..	Not yet	1924	Part 1922	1924	1910	Part 1913
Contact conductor ..	—	Overhead	Overhead	Overhead	3rd rail	Overhead
System	—	D.C.	D.C.	D.C.	D.C.	1 phase 16 ~
Volts on conductor ..	—	1 500	1 500	1 500	850	12 000

* These figures are merely an indication of the through trains shown in Bradshaw's Continental Guide, but Fig. A and Table A facilitate the location of places and show the through passenger part of the services which are electrically operated.

an average loss of 12 per cent between substations and trains; while the Norfolk and Western Railway in America (single-phase at 11 000 volts) with three-phase motors shows similar economy but has an average loss of 1½ per cent in the circuit. The 650-mile Milwaukee line buys water power at under 0·3d. per unit, and energy is cheaper than interest, etc., on more copper to reduce the average loss. The Norfolk and Western hauls coal 29 miles and can sell at the top end of its gradient every ton saved from its transport. Therefore it pays the railway to put transformer substations 5 to 7 miles apart and enough copper to bring down the average loss to 1½ per cent. In a report widely circulated by its author the statement was made that if he were to use single-phase current in South Africa at 11 000 volts as is done on the Norfolk and Western Railway, his substations would be 50 miles apart. The Norfolk and Western Railway is 29 miles long, and the substations if put at 50 miles apart would be over 10 miles beyond each end, which would be absurd. It is stated that the train lighting on the Midi Railway is supplied by a generator on the locomotive at 120 volts. We have a good deal of 25-volt lighting for train service with generator and accumulators on each carriage, and I have seen as high a pressure as 60 volts used for lighting. If the author provides batteries to light the trains when the locomotive is not connected, it seems to me that he must have a 60-cell battery in each carriage. The curves for the Paulista Railway show no regeneration below 42 kilometres per hour for passenger trains, and none below 22 kilometres per hour for goods trains. The author banishes regeneration from the Midi Railway because the complication is greater than the advantage, but in my opinion it all depends on the nature of the line. Regeneration in actual regular service works splendidly, but in an emergency it has proved worse than useless. In one case a train in North America ran away and was wrecked. The time limit available for that driver to get his regenerative brake into action was 30 seconds, but this period had passed before he knew the emergency had arisen. The driver has to ascertain the field current and adjust it to the speed of the train before he throws in the armature to let it regenerate. It is an operation which throws a great strain upon the driver in an emergency, even if he realizes that the necessity for action has arisen. When studying the paper I found it necessary to prepare a map (see Fig. A) and I examined the frequency of train services and speeds (shown in Table A). These may prove useful to others.

(10 *January*, 1924.)

Mr. J. Sayers: The first matter to which I should like to refer is the question of induction on single-phase lines. When the directors of the Midland Railway entered into their experiment on the Lancaster, Morecambe and Heysham line, they did so in order to see what was necessary on a main-line electrification and what should be avoided. At that time there was no practicable direct-current system at a pressure higher than 600 volts, and it was therefore necessary to adopt single-phase traction at 6 600 volts. As a matter of fact that line, which was opened in 1907, was the first single-phase high-tension line in the British Empire. The matters which were to be chiefly investigated were, first, the trying-out of single-phase apparatus; secondly, the troubles which we expected to get from induction on communication circuits; and thirdly, the practicability of overhead collection at high speeds. The Midland Railway is pre-eminently a trunk telephone line; it carries what is called the "backbone line" of the Post Office to Scotland. It was very clear, therefore, that they had to make quite certain of their ground before they adopted any system of main-line electrification. The scheme for counteracting induction used on the Midi Railway was considered some years ago by the Midland Railway and patented by me in 1909, but it was not adopted because it seemed to me that to erect special wires carrying current to do nothing else but overcome the inductive interference from the contact wire, was not a practical solution. I should imagine that the line upon which it has been tried on the Midi Railway is a single line. This is, of course, a comparatively simple proposition; but if it were attempted to erect these counter-inductive wires overhead on, say, four tracks passing through junctions, cross-overs, and so on, I think it would become a very complicated problem indeed. The next method which I tried was quite successful, but, I am afraid, equally impracticable. The idea was to charge the telephone wires with an E.M.F. 180° out of phase with the contact wire to earth, and to charge the two wires through a condenser, the other end of the transformer winding being to earth. This was the only method with which we ever got silence in our very perfectly revolved telephone circuits. It is not very easy, however, to see how it could be applied to a large number of trunk lines. For that reason we gradually came to the conclusion that the inductive trouble with main-line working was a very serious matter indeed; and as higher pressures became practicable for direct-current work we formed the opinion that direct current had the advantage that the inductive trouble was very much less. The same reason has clearly influenced the Midi Railway, although we were quite unaware of it at the time. There is a very striking similarity between the best means we have been able to design for the contact system and that of the Midi system. An overhead system is far and away the simplest method for main-line working. The chief trouble here, however, lies in the design of "pull off" insulators, whose object is to hold the wire in the correct vertical plane for collection. These insulators are the only source of trouble which we have experienced and I have therefore tried gradually to eliminate pull-offs. On curves this is quite simple, because the messenger wire is kept on one side and the droppers keep the wire to the curve of the rails. On a tangent track we stagger the messenger wire across and this means that the droppers hold the wire alternately on the sides (see Fig. B). The rigidity of the contact wire in a horizontal plane against storms and wind is actually greater than where a pull-off is used at every gantry. Fig. C shows the results of tests with the old and new arrangements indicated in Fig. B. I should

like to know what the author has done in connection with avoiding joints in the contact wire. Joints are a weakness in every way, and generally they involve frequency surges. We put in an inductance leak to draw off static charges. It may surprise those who have had no experience with a line of this kind to

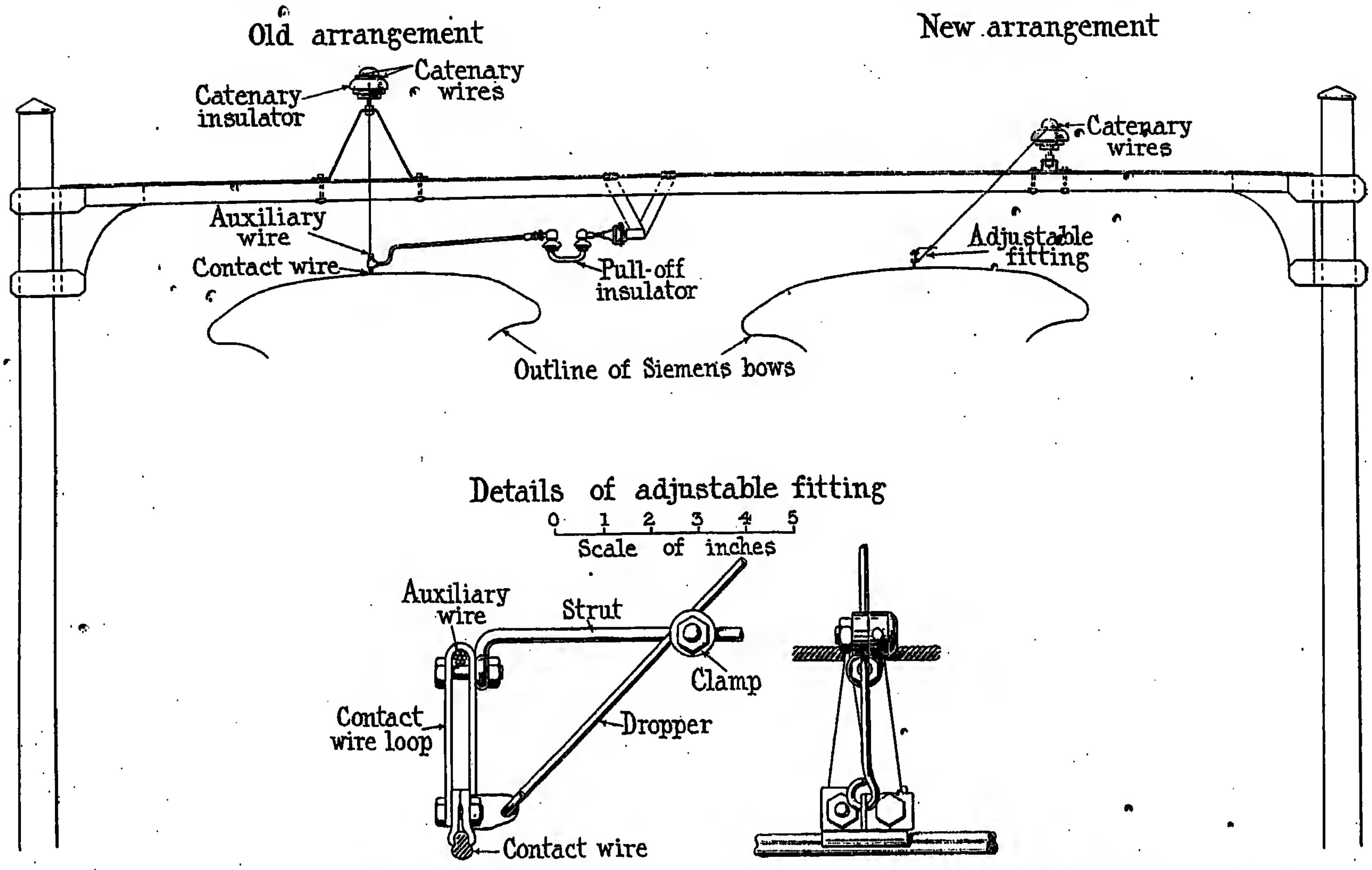


FIG. B.—Old and new arrangements of overhead wiring on a 30-chain curve between gantries on the Lancaster, Morecambe and Heysham line.

extra inertia in a vertical plane, which is the very worst thing possible in high-speed current collection. The author did not touch on the question of lightning

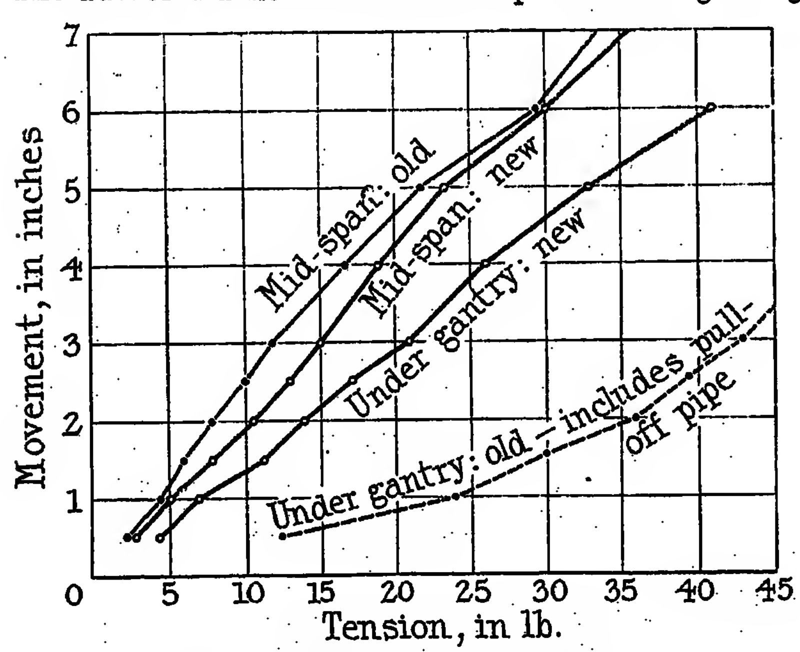


FIG. C.—Relation between upward movement of contact wire and tension on a 30-chain curve.

protection, but this is rather important. We have put in a set of Moscicki condensers to take charge of very high-frequency surges, and a Giles valve for moderate-

know that the static charge on a wire, say, 22 ft. above the ground is very high indeed in certain states of the weather. During the erection of the line we had numerous reports of men receiving shocks, although there was no connection with the power house. The last point to which I should like to refer is that of the power supply to a railway system. Evidently the Midi Railway is going to have the great advantage of a combined railway and industrial generating station and network supply, at 50 periods. In this country there is at present a strong prejudice against 50-period large rotary converters. But as the Midi Railway proposes to adopt mercury rectifiers I take it that these will replace the rotary converters. Whether 50 periods can be used for traction purposes and, therefore, whether the railway systems can be joined up to the general power supply—a very desirable thing in itself for economy's sake—has not been settled. Possibly it would be better to pay the extra cost of current and either run frequency-changers from the general supply or allocate certain stations and power supply systems to traction, than to run the extra risk of shut-downs on a big transport system.

Mr. F. Lydall: In this country we have seen the electrification of railways develop almost entirely along the lines of urban and suburban work, and that has necessarily been mainly confined to a direct-current

multiple-unit system operating at a low voltage. The Midi Railway, on the other hand, has had a much more diverse and wider experience. It commenced with low-voltage direct current, and developed along the lines of single-phase alternating current. For locomotive work the single-phase system was first employed, followed by high-tension direct current. The account of this period is of great value to us in foreshadowing the points which may have to be considered when we have to deal with main-line electrification. In one respect, however, the experience in France does not strictly apply to what may happen in this country. The Ministry of Transport has determined the system on which main-line electrification in this country is to develop, viz. direct current principally at 1 500 volts, with occasional exceptions. We have also to consider, however, as an exporting country what advantages there may be in utilizing other systems under other conditions in other countries, and therefore the experience gained on the Midi Railway is of value as influencing our consideration of the possibility of single-phase traction on railways abroad which may be equipped with machinery and apparatus manufactured in this country. The chief trouble with the single-phase system on the Midi Railway seems to have been inductive disturbance. A very full account of these troubles, of the tests made, and of the attempts to overcome them was published in the French technical Press (*La Technique Moderne*, March and April, 1919). The author gives general reasons why the French Government decided to standardize the direct-current system, and as our Ministry of Transport came to exactly the same decision we naturally uphold that decision. I think it should be recognized, however, that the single-phase system cannot be considered as having no place in railway electrification. As an example I may mention the electrification of the Virginia Railway in the United States. According to published accounts of this scheme the locomotives will have a maximum capacity of 20 000 h.p. For this output the electrical input will be about 17 000 kW, and if the d.c. system were employed with a distribution pressure of 3 000 volts the current taken by the locomotive would be about 6 000 amperes. No doubt it is possible to collect this current from an overhead line by using a sufficient number of collectors, but the cost of providing and supporting overhead conductors of sufficient section to carry such a large current would be very high if not altogether prohibitive. The single-phase system with a distribution pressure of, say, 15 000 volts would avoid this difficulty. A short time ago I was privileged to inspect various parts of the Midi Railway system. One of the substations which I visited contained three single-armature rotary converters, the other two mercury rectifiers. The rotary converters were, of course, 1 500-volt, 50-period machines, and the point which greatly impressed me was that practically no steps had been taken to guard against serious flash-overs on the rotary armatures themselves, except the provision of high-speed circuit breakers. The brush gear was as simple as on an industrial 250-volt motor. I understood that they relied entirely upon the high-speed breakers to prevent flash-overs. One or two flash-overs had occurred but these were due to short-circuits on the overhead line immediately outside the substation, so that the current must have been very considerable and the conditions very severe. When such flash-overs occurred the machines had to be shut down and the commutators cleaned up, and this probably took about 30 to 40 minutes. We should not, I think, be prepared to face this risk on lines in this country. Another thing that I noticed was that there was no guard of any kind round the rotary converters. In place of lightning arresters, flash suppressors of the Capart type were used. I should be glad if the author would say whether these are to protect the machine and apparatus in the substation from lightning troubles, or to prevent flashing-over due to surging caused by short-circuits. The rectifier substation contained two rectifier sets and a great deal of other apparatus. The rectifiers were the smallest pieces of apparatus in the substation and were remarkably compact. I should be glad if the author would give some additional information about them, as there is a general feeling in this country that they are liable to give trouble from backfiring. In a recent article the efficiencies of these rectifiers were stated to be as follows: On overload 95 per cent and at quarter load 93·2 per cent. I do not think that these figures show any substantial improvement on a really up-to-date 1 500-volt 50-period rotary converter. The general design of the locomotive as regards the method of mounting the motors on the axles is not very special. The interior of the locomotive struck me as being well arranged. There is a central aisle from end to end, on each side of which the control equipment is housed in compartments. The main motor-generator, which provides forced draught and auxiliary power for general purposes, is located in the centre of the aisle and is quite easy to get past. The arrangement seems to me to be satisfactory, except that the back of the switchgear is not very accessible, and this may rather tend to increase the maintenance costs of the equipment as it stands. It is interesting to note that regenerative braking has been abandoned in favour of rheostatic braking, but I should like to ask whether that does not involve a considerable increase in the weight and volume of the resistances into which the return energy has to be passed, and also whether any arrangement is made for forced draught on these resistances to prevent them from overheating. Can the author give any figures of the expected return of energy by regeneration? I do not think that we should take this decision of the Midi Railway as implying any doubt as to the value of regenerative braking under suitable circumstances. There is, I believe, no idea of abandoning the system on the Chicago–Milwaukee Line, where it has been in use ever since operations started; and in the latest locomotive being built by the General Electric Company of America for the 3 000-volt Mexican Railway system, provision is made for regenerative braking. In regard to the design of the experimental passenger locomotives, it is noteworthy that Sir Vincent Raven in his paper read last year before the Institution of Mechanical

Engineers, suggested for the locomotive oscillations which take place a cause quite different from those mentioned by the present author. Sir Vincent suggested that these oscillations took place in the United States and not elsewhere because the rail joints in that country are staggered alternately from side to side, and that this may at certain speeds of the locomotive set up sideways and vertical oscillations which will synchronize with the natural frequency of oscillation of the locomotive. It is difficult, of course, apart from actual experience and very elaborate experiments, to say whether one cause rather than another is definitely more likely to give rise to the trouble, but it is certainly worth while taking special note of the fact that both Sir Vincent Raven and the engineers of the Midi Railway took their courage in both hands and, in spite of the alarmist warnings of the engineers of the United States, built experimental locomotives which were symmetrical, and in both cases have found that their courage was fully justified and that no trouble was experienced. I should like to draw attention to a long account of the working of the six experimental single-phase locomotives built by the Midi Railway, in the 14 December, 1918, issue of the *Revue Générale d'Electricité*. The conclusions drawn in this article from the practical and theoretical discussion are very briefly as follows: There are five sorts of oscillations in connecting-rod locomotives, and such locomotives must have all these different kinds of oscillations to a varying extent as the speed increases. The concluding remark is, I think, illuminating: "Finally, geared locomotives are free from all these." On the general question of the height of the centre of gravity I am not satisfied that it is necessary to go to any elaborate and costly construction of the motors in order to secure a high centre of gravity of a locomotive. A high centre of gravity is undoubtedly of practical utility, but it must be admitted that this height is dependent on the general construction of the locomotive rather than on the position of the motors in relation to the axles. Certainly not much is gained by merely lifting the motors above the centres of the axles; in the passenger locomotive built by Sir Vincent Raven, the centres of the motors were 21 inches above the centres of the driving axles, but this had the effect only of raising the centre of gravity of the whole locomotive 3½ inches, compared with what it would have been if the motors had been mounted level with the axles.

Mr. H. N. Gresley: The author has rendered great service in bringing so prominently before us the far-sighted and wise policy of the French Government in allowing the railway companies to supplement their load by an industrial load, thereby improving their load factor. In England the position is, of course, quite different. The railway companies who wish to electrify will have to get their current from one of the power companies, or else have very great difficulty in making out a case—as we have seen on one of the lines which has recently started electrification. It would be interesting to know whether statutory areas of supply are allocated to various power supply companies in France. The electrification of railways is much more attractive in France than in England, because coal there is so much more expensive, and the Midi Railway uses water power. In this country a comparatively small zone is electrified—in most cases where there is a very dense suburban traffic and the load factor is, in consequence, very poor. There is a tremendous number of trains during the rush hours of the morning and the evening, and for the rest of the day there is a comparatively small traffic in cases where only the suburban passenger trains are worked electrically. On some of the railways which have been electrified in that way a procession of steam-drawn passenger and goods and mineral trains may be seen going over the electrified lines. If the cost of current were reduced and if the electric lines were extended to 40 or 50 miles, it would be practicable to take off the steam locomotives and use to much better advantage the capital which has been spent in a third-rail or overhead equipment. This would result in a very much steadier load and a much improved load factor. At present the power supply companies should be able to supply current more cheaply than a railway with only a suburban traffic at a poor load factor; but if the load factor were improved I suggest that a railway company should be able to have its own generating station and produce power more cheaply than a power company. A railway company with all its many and varied properties in the way of lands, lines, steamships and hotels, etc., would offer very much better security for debenture holders than a company which has only a power station. It could therefore raise money at a lower rate of interest than a power supply company could. Again, if a railway company had electrified the bulk of its main lines and obtained its power from a power company, it would practically be putting into the hands of that company for a period of 30 or 40 years—they require long agreements—the whole of the power for operating that railway. The railway would have no voice in the management, and would derive no benefits from the economies which might be produced, as its agreement would be at a fixed rate. I suggest that it might be possible for railways when electrified to make some co-operative arrangement with the power companies by which the railways themselves would have a direct interest in the power company. Possibly they might assist in financing the extra equipment required, in which case they would require to have a voice in the management and some representation on the directorate of the company.

Mr. A. T. Dover: In connection with the substations equipped with rectifiers and rotary converters, would the author give, if possible, the all-day efficiencies of these stations under similar loads, and also figures for the pressure regulation? Also, would he indicate what staff is required in the two classes of substations, and say whether periodic overhauls of the rectifiers are necessary? Do the ripples in the d.c. pressure cause any extra wear in the gears or in the motor bearings? The author's opinion would be appreciated on the question of the practicability of making fully automatic the rectifier substations supplying branch lines having light traffic. Has this been tried out in practice, and are the results as favourable

as those obtained with automatic rotary-converter substations? At the top of page 216 it is stated that the low-tension auxiliary service set on the passenger locomotive is rated at 72 kW. This is probably a misprint, as 72 kW is rather excessive for a locomotive equipped with four 350-h.p. motors. In dealing with track bonding, the author mentions that a number of experiments have been carried out with different types of bonds, the type finally adopted being one which bonds the fishplates to the rails, the bond being fixed by means of split pins and through bolts. Can the author give any further details of that system? The general practice in this country is to fix the bonds by hydraulic pressure. In describing the motor-car for suburban and branch-line services the author states: "The tractive effort is transmitted from the truck frame to the swinging bolster through articulated drawbars instead of the ordinary friction plates." That seems to be a new method, and I should be glad if the author would describe it more fully.

Mr. R. L. Morrison: At present in connection with the Midi Railway electrification scheme there are altogether five substations equipped with mercury-arc rectifiers, the total capacity amounting to about 19 000 kW, representing 16 sets each of 1 200 kW. These have been installed, I believe, where the loads are the severest, i.e. where the inclines are greatest. They are designed to deal with pressures up to 1 800 volts on the d.c. side. Rectifiers are specially suited to traction conditions, due to the fact that they are capable of handling extremely heavy momentary overloads and heavy short-circuit conditions. In fact, one is hardly conscious when near such plant that short-circuits have occurred, except for the tripping out of the circuit breakers. It will be noticed from the lantern slide which I shall now exhibit that for long periods the overload capacity is not great, but for short periods extremely heavy loads amounting to several hundred per cent overload can be handled, and under some circumstances for as much as $2\frac{1}{2}$ minutes at a time. It is the property of the rectifier in this respect that makes it so suitable for these particular conditions. The next slide shows a short-circuit curve taken on one of the Midi rectifiers. The normal current rating was 400 amperes and at the time the test was made the d.c. pressure was 1 800 volts. It will be noticed that before the circuit breaker cleared, the current rose to 8 700 amperes, or 22 times the normal value. Sixty similar short-circuits were applied for two days in succession, after which the cylinder was opened up and found to be in precisely the same condition as when sealed up prior to the test. Mr. Lydall has referred to the high-speed circuit breakers used in connection with some of the rotary converters. Similar circuit breakers are used in connection with the rectifiers. As seen from the next slide, this breaker is of novel design, the object being to cause the arc to spread out right round the circuit breaker. This is obtained by providing a heavy magnetic blow-out field round the switch, and from the next slide the effect of this field on the path of the arc is clearly seen. The switch is designed to open in about 1/100 second, and when the photograph was taken the short-circuit current amounted to 8 500 amperes. The next slide shows the same switch opening with 8 700 amperes—in this case the arc has travelled a good deal further round the switch. The total resistance in the circuit at the time was 0·025 ohm, while the switch opened in 1/60 second. The next slide is a photograph of one of the Midi sets. It consists of two cylinders each rated for 600 kW, with a vacuum-pump set common to both. The vacuum-pump set has recently been to some extent simplified, especially for automatically operated equipments, and the vacuum gauge in such cases would be of the direct-reading type, in appearance similar to an ordinary voltmeter. The next slide gives the test figures of the Midi sets to which Mr. Lydall has already referred. The efficiency curve includes all losses. The power factor at $\frac{1}{4}$ load is lower than what might be expected in the normal case and, in this instance, is due to the fact that a 12-phase connection is utilized instead of a 6-phase, which results in a rather complicated set of windings. The inherent regulation of these particular sets, taken on the basis of a constant primary pressure, amounts to a trifle under 3 per cent. The next slide shows efficiency figures obtained on another high-tension traction rectifier designed for 1 200 volts (d.c.) which has been running for some years at Ekeberg, near Christiania. The power factor is very high, dropping only to 90 per cent at $\frac{1}{4}$ load, while the efficiency is also very high. Automatic control of rectifiers has been highly developed and excellent results have been obtained with relatively few relays. The connections are simple and, in spite of what has been said by one speaker relative to the unsatisfactory operation of rectifiers, it can now be definitely stated that the earlier troubles have been so far eliminated, by improved design and other conditions, that the rectifier is now well on the road to being as reliable in operation as any other form of converter.

Mr. C. E. Fairburn: I do not think the author gives the impression that the regeneration system has been abandoned because it was in any way inefficient or because it did not work properly. Rheostatic braking is preferred to regeneration, because the mercury-arc rectifier substations have been placed on severe grades. It is impossible to regenerate into a mercury-arc rectifier, and when regeneration is started the return current flows to the nearest rotary-converter substation. In consequence the distance between the locomotive and the rotary substation is often very great, with the result that the consequent voltage on the line is very high, and this affects all the apparatus. The lantern slide shows a skeleton diagram giving the main connections. The main motor armatures are connected two in series with a small buffer resistance across the line. The fields of the motors are separately excited from a variable-voltage generator on the field of which there are some reverse turns in series with the regenerated current. This helps to regulate the current-rushes. The actual control of the regenerative braking is by varying the shunt field on the variable-voltage generator. The next slides show the relation between torque and armature current at a line pressure of 1 500 volts, and also at varying voltages. An auto-

matic relay is provided to prevent the armature current becoming more than 3·5 times the field current. The next slide shows the results of some tests taken last year. Actually the locomotives had been regenerating some months before that, and they have been regenerating satisfactorily up to the present date. These tests were carried out on a gradient at Capvern between Toulouse and Tarbes. This gradient has a constant slope of 3·3 per cent for 11 km, and it will be seen that a considerable amount of energy was regenerated. There is no trouble with this system of regeneration. The switch is thrown over to "regeneration" and an ammeter is provided showing the field and armature currents side by side. The only rule which the driver has to obey is that the needle for the field current must not pass that for the armature current. If it should do so, the automatic relay comes into operation. The driver operates the master controller exactly as if he were using it for driving the locomotive.

Mr. G. W. Partridge: The author states that the system "is protected against pressure-rises by earthed reactance coils with iron cores, and against steep-front surges by Capart apparatus consisting of mica condensers branched between two inductive coils, one of which is shunted by a resistance." I should be glad if he would describe this arrangement more fully. The paper states that the protection of d.c. machines is provided for by high-speed circuit breakers and an earthing device composed of a condenser shunted by a resistance, but I should like a little further information on this point. Does the term "high-speed" mean that the actual circuit is opened quickly at the moment the circuit breaker commences to start, or does it mean that a circuit is opened instantaneously when any disturbance occurs? I entirely agree with Mr. Lydall that in the supply to a railway, if these circuit breakers are set to open immediately there is any trouble on the system, various sections of the railway are liable to be shut down. Shock upon shock is thrown upon our station supplying suburban railway systems, and if the main circuit breakers opened every time there was a short-circuit, it is certain that the supply would be badly affected. I can conceive difficulties in the way of giving a commercial supply in certain districts where there might be rather heavy pulls on the railway, which would, I imagine, upset the regulation or cause drops in pressure on the commercial supply; whereas pressure-drops in moderation would have very little effect on the working of the railway. Has the author considered an apparatus for limiting the maximum demand in certain districts? If the charge made to the Midi Railway for current is on the principle of so much per kW of maximum demand with an additional charge per unit, the lower the maximum demand can be kept the better. I believe that this system has been tried in America with some success. Mr. Gresley seems to think that the supply company's tariffs are too high to-day. My experience is that most supply companies to-day are charging the public almost pre-war rates. In the case of railways, everybody will appreciate what it costs to travel and to send goods by rail at the present time compared with pre-war days. I can conceive that under certain conditions it might be to the advantage of a railway company to own the power station, but Mr. Gresley overlooks the fact that railway companies have no powers to sell electricity to the public, and so long as the supply companies have powers to sell electricity for its various uses, and so long as from year to year these various uses are multiplied, there may come a time (not far distant) when the supply companies will be selling electricity to certain users under special conditions at lower rates than those charged to the railway companies. I therefore fail to see how a railway company can generate electricity more cheaply than a large supply undertaking with various users of its supply. I can assure Mr. Gresley that in making a contract with any supply company there is very often a clause to the effect that the railway company should have the benefit of any improvement in the art so long as the company agrees to pay reasonable interest on the capital expended. Then, again, I think that it would be quite a reasonable condition in a contract if the charges were revised every 10 years, so that the railway company would not be left in the hands of any one supply company over a long period without power to modify the rates of charge if circumstances justified revision. The railway companies may, I think, safely leave the supply of electricity in the hands of those who have spent their lifetime in the industry.

Sir J. A. F. Aspinall (*communicated*): It is gratifying to find that the French Commission came to the conclusion that their traction system should be direct current at 1 500 volts, as this is the same as that recommended by the Electric Railway Advisory Committee in this country. It is also interesting to know that some of the French companies wish to keep to the use of the third rail although they will use 1 500 volts. The nearest present approach to this in this country is on the Manchester and Holcombe Brook line of the London, Midland and Scottish Railway, where 1 200 volts is carried on a side contact rail with great success and security. The author's praise of the mercury rectifier is very encouraging. The breaking of axles is being wisely overcome by bolting the gears to the driving wheels. Locomotive engineers have long been familiar with the fact that any stiffening of the axle at any one point due to anything being bolted round it may cause fractures, and more especially when a keyway is added. Uniformity of flexibility throughout the axle is a safeguard. Am I right in assuming that the author would accept regenerative braking on those railways where there are long inclines? I am in complete agreement with the author's remarks in regard to locomotive construction. The introduction of reciprocating movement by the use of outside rods is most undesirable. As in the first place we have the rotary motion of the motors, to convert this into the reciprocating motion of the rods, and then reconvert it into the rotary motion of the wheels, has always appeared to me to be a mechanical abomination. There are other and more attractive designs, and when this great French electrification of railways is more advanced we shall see these preliminary difficulties swept away very rapidly on account of the large field for experimental work. For instance, the locomotives

with twin vertical motors to which the author refers, have some very good points, and had this method of driving been applied to engines specially designed for it, the details would have worked out in a more advantageous way. The author also recognizes the advantage of a high centre of gravity. In conclusion, I quite agree with his view that the generally-held opinion that the symmetrical wheel-base makes for unsteady running is a fallacy.

Mr. J. Dalziel (*communicated*): It may be remembered that the late Midland Railway in its Heysham–Morecambe–Lancaster installation was the first to put single-phase traction into operation in this country. Various officers of the Midi Railway, in fact, visited that installation whilst their own scheme was under consideration. The adoption of a single-phase system by both railways was dictated by the same considerations, viz. that for main-line work the overhead collector system promised the best results and appeared to be the most feasible, and, as things were then, the single-phase system was the only practically applied system with which an overhead line could be used for heavy traction. As high-voltage direct-current systems working off an overhead wire are now available, and as the arguments against single-phase current, of intensified induction effects on weak-current lines and neutralization of the advantage of substation simplicity when 50-period supply is used, apply equally in this country as in France, one has to agree that there is no longer any substantial vogue for the single-phase system in this country, even though one must still contend that it has certain advantages in heavy traction which are of some importance, and that with modern development of its apparatus there is no reason why it should not attain a standard of reliability and of low cost of maintenance nearly equal to that of direct-current apparatus. It is stated in the paper that certain companies wish to adhere to the use of the third rail and use 1 500 volts thereon; there is a similar sentiment among some engineers in this country, and it would be of interest if the author would give the reasons which dictated his own disagreement from this policy and his adoption of overhead collection. In the meantime the third-rail system is practically standard in this country for urban and suburban work, chiefly due to the necessity for connecting up, and inter-running, with existing third-rail installations. It is still a matter of controversy whether it should be extended to main-line work or the overhead system preferred. The latter is the practice in nearly every country and railway that has instituted main-line electrification, and, speaking for myself, it would seem to be the obvious course, for while an overhead contact line can be applied without break of continuity throughout all lines and sidings, the third-rail system is subject to interruptions where it must be reinforced by lengths of overhead collection. Gaps must always occur in the third rail at points, crossings, etc. Multiple-unit passenger trains can bridge these or coast over them, but locomotives certainly can neither bridge them nor always coast over them, especially in freight service, where they occur, almost of necessity, at the very points where a shunting locomotive will have to do most of its starting and stopping. It would seem that the question resolves itself into this: If an overhead conductor can do all the work, and the third rail cannot and requires overhead assistance—with some complications—at intervals, why use the third rail at all? It may be that these considerations, with perhaps others, carried weight with the author. On page 214 the use of synchronous condensers of 60 000 kVA total capacity is mentioned. If the purpose of these is to correct power factor, as presumably it must be, it would be interesting to know whence comes the very low power factor which is implied by the use of these machines and their very high capacity. Presumably it is the industrial load which gives rise to their necessity, as one would hardly expect a purely traction load fed through rotary converters and mercury rectifiers (which are not comparably much lower in power factor) to need such correction. Another question that might be asked in this connection is why moving machines were used in preference to static condensers? The answer may be that the latter were not developed to the point of practical efficiency at the time the author had to make his decisions. The author's testimonial on pages 214 and 215 to the satisfactory operation of his 1 500-volt 50-period converters and of his 1 500-volt mercury rectifiers is particularly valuable if, as one believes to be the case, this voltage is so far the highest in practical use on both types of apparatus. One is given to understand that mercury-rectifier apparatus of still higher d.c. voltage is in course of installation. With regard to sectionalizing (referred to on page 215) it would be interesting to know what length of section is cut out automatically when a breakdown occurs. It is also not quite clear whether this cutting out is done on the high-tension line or the contact line. If the former, one would also like to know into what length of section the contact line is divided, and whether the sections are automatically isolated. On page 216, in the description of the first two types of engine, it is mentioned that the couplings and buffers are fixed to the truck frames and not to the locomotive body proper, as is more usual, the object being to avoid the transmission of tractive effort by the centre pins. It would appear that the author's method would exercise some restriction on the free radial play of the bogies in passing round curves. Has any such effect been observed? Regarding the author's remarks as to regenerative braking, I should like to ask to what extent the comparatively very small value of the regenerative current on the Midi Railway has influenced the decision arrived at. There is no question that unless the value of the regenerated current is substantial, the additional control gear and additional complication introduced will restrict its use to those cases where gradients are very heavy and the value of the current is unusually high. It is clear from the author's remarks that the saving in brake-shoe and track wear and tear claimed for regenerative braking is being obtained on his very heavily graded line by the simpler method of rheostatic braking. The author's express locomotive and his exposition of the characteristics governing the design of such locomotives are

of special interest. One is glad to note that he objects to rod locomotives, on the grounds that they give rise to "stresses leading to breakage of rods, cranks and even of the engine frame" and, the expressed opinions of certain of our leading technical journals notwithstanding, it will be agreed that in these remarks the author expresses the general consensus of opinion with regard to such locomotives. He does not, of course, suggest that there is no rod locomotive giving modified satisfaction, but only that it is a species which is dying of its own infirmities and had better never been invented. The author's vertical motor is a new departure which has the advantages, at least, of helping to raise the centre of gravity and of putting the commutators and brush gear into the cleanest and most accessible position available. I doubt whether the author's bevel gear can have any advantages over, or even be equal to, straight spur gear as regards either efficiency or maintenance, and it is generally accepted that bevel gear requires greater accuracy in alignment and setting than straight gear. The author's views as to the satisfactory operation of symmetrical wheel-base locomotives are rather opposed to those held by traction engineers generally with reference not only to electric but also to steam locomotives; it is generally considered that for trailing purposes a centrally mounted bogie is not so suitable as a single-axle or two-axle truck pivoted forward of its centre. Though the riding qualities may be sufficiently satisfactory both ways, it is certainly the case that some engines with a leading bogie and a trailing axle pivoted as mentioned above ride much better with the bogie leading than with the bogie trailing. Of course the inferiority may arise more from the fact that the single-axle truck is a bad leader than from the fact that the bogie is a bad trailer, but it is at the rear end that it shows the most. The author's locomotive will certainly be one of the most interesting so far put on rails, and if its riding proves his contentions it will not only mark a step forward in electric locomotive design but relieve a certain amount of anxiety on the part of electric locomotive designers on the subject of wheel-base symmetry.

[The author's reply to this discussion will be found on page 230.]

North-Eastern Centre, at Newcastle, 26 November, 1923.

Mr. H. W. Green: It is unnecessary to go outside our own country (or, in fact, outside our own locality) to learn of the reliability and successful results obtained with electric traction. The few lines on which this system has been adopted in this country have proved such a success that one is apt to wonder why further electrification is not taking place more rapidly. Every railwayman is proud of the steam locomotives now in service and of their performances, but they compare very unfavourably with electric locomotives. A number of economies which are effected by the adoption of electric traction are enumerated by the author, and these cannot be too often repeated. There are others not mentioned which are worth adding. Turntables would be unnecessary, due to the locomotives being arranged for driving from either end. The number of locomotives required would be reduced owing to the longer time they could be kept in service. Trains could be double-headed and still have a crew on only one engine. It would be interesting to know what savings the Midi Railway have effected in this respect and what they anticipate on the complete scheme. The limit to the size of locomotives has almost been reached and it would seem that if heavier trains and the existing or higher speeds are to be maintained, then the only solution is electric traction, in which the motive power is accommodated in considerably less space and is reduced in weight. This point was very clearly illustrated in a paper by Sir Vincent Raven a short while ago. The present tendency appears to be to consider electric traction for lines over which there is an assured traffic, but the fact that electrification invariably results in increased traffic should not be overlooked. This applies more to the suburban lines, and it would be well to bear this in mind in connection with lines over which there is not a large traffic. A better and more frequent service would undoubtedly lead to the opening up of many suburban areas and reduce the overcrowding in many of our towns.

Mr. F. H. Williams: In considering electric traction in a general way it has been fairly common to consider Continental practice as essentially based on the use of a.c. motors for transmitting the power to the driving wheels, and British practice as favouring the use of d.c. motors. This generalization has led to the impression that engineers in this country were not prepared to consider the possibilities of a.c. traction motors; but this is quite erroneous, and in considering any new schemes it is usual for both possibilities to be carefully explored and the decision to be arrived at purely on merit. On page 214 the author mentions that locomotives are to be fitted with gear for collecting current from a third rail as well as from an overhead conductor. It would be interesting to have some information on this matter, and also to learn what type of third rail has been standardized, and whether any special steps are being taken to prevent accidental contact, both with the third rail and with the collector shoes. It is by no means easy to design a third rail which will give reasonable safety when used with 1 500 volts. With regard to the cam-shaft control, how does this compare with the ordinary contactor control, and is any extra difficulty experienced in starting heavy trains on gradients when the rails are greasy, i.e. does the cam control return to the starting position as quickly as the ordinary contactor control? In regard to bonding, were the troubles referred to in the paper due to mechanical failure or to bad electrical contacts? I do not think the form of bond described is much used in this country, a ribbon type or stranded bond fitted under the fishplate being usually adopted.

I have seen a ribbon bond which had been submitted artificially to over a million vibrations and was still practically as good as when the test was started. If the troubles experienced were due to poor electrical conductivity, I should like to know what they were and how they were discovered. Has the author found any satisfactory method of measuring the conductivity of bonds, using the current flowing in the rails? So far as I am aware, there is no satisfactory method of doing this, and the only way of making a satisfactory bond test in situ is to use a special form of "Ducter." Measurements made with this equipment are very satisfactory and reliable but, unfortunately, require the rail to be made "dead." Badly bonded joints can readily be detected in frosty weather by an examination of the joints directly after a train has passed, as the frost or snow will have been melted round the joint.

Mr. R. J. H. Beaty: The greatest novelty mentioned in the paper is the rotary converter to work on a 50-cycle supply and give 1 500-volt direct current, but it is not described in detail, and the fact that it has a radial commutator is not even mentioned. What is the peripheral speed of this commutator? This is really a reversion to d.c. turbo-generator practice, which was thought to be extinct. Perhaps the day is not far distant when we shall completely enclose these machines, fill the case with compressed air, try to run at a higher voltage per commutator bar, and so reduce the peripheral speed. These abnormal types would not be necessary were it not that absurdly high frequencies have been standardized in most countries. We are told that a voltage of 1 500 has been chosen to allow the third-rail system to be used, but is this system necessary or desirable? It may be all right for tube or overhead railways where there are no level crossings and few junctions, so that the rail can be fairly continuous, but on most ordinary railways there are numerous private crossings leading to fields, each of which crossings necessitates a break in the third rail. Would not this be rather distressing at 90 miles an hour? A drop of 20 per cent in the line voltage under normal service is not a testimonial to the wisdom of standardizing that pressure at 1 500 volts, if the high-speed breaker can be relied upon. It is rather disappointing to hear that regenerative braking has been abandoned, as one would expect that a considerable amount of power would be regenerated on the 1 in 25 and 1 in 30 gradients mentioned in the paper. The first two types of locomotives are fitted with motors of the wheelbarrow type, a survival of the unfit. In these the driving force is vertical as in some of the pioneer steam locomotives, but this method was discarded by Stephenson over 90 years ago owing to the whole engine being rocked on its springs. In this type of motor, however, the rocking is reduced by having half the weight unsprung, a state of affairs which can hardly be accepted as the final solution. The 4–6–4 express locomotive is one of the most interesting machines mentioned in the paper, and its evolution is a step in a direction in which progress has been all too slow. The author's remarks on nosing will take a permanent place in the history of electric railways. The 4–8–4 locomotive is said to be capable of pulling a 600-ton train, presumably as a test load only. Far too many passenger trains have been broken in two in recent years, and, so far as this country is concerned, 300 tons should be the limit for any passenger train. I think that if we had an electric locomotive capable of taking a 300-ton train up a 1 in 100 gradient continuously at 50 miles an hour our booked speeds could be considerably improved. At the present time we have to compete only with the inefficient steam locomotive, the power of which, as is well known, is limited by the size of boiler that can be built within the loading gauge; but the future may bring forth an internal-combustion locomotive free from this limitation and capable of giving a constant pull over a fairly wide range of speed. I think it is desirable that British engineers should study the conditions which exist on their own lines and deal with them in their own way without being unduly influenced by foreign practice or limited by standards prematurely fixed.

Mr. H. R. J. Dunthorne (*communicated*): The outstanding feature of the paper is the magnitude of the undertaking described therein, and one would have liked to have asked the author for some information as to the estimated cost of the work divided over permanent way, rolling stock, power stations, substations and distribution. It would be interesting to know how the system adopted compares with straight single phase using e.h.t. distribution with step-down transformers on the locomotives, and series motors, in respect of first cost, running costs and overall efficiency; and also how the work is being financed, i.e. out of revenue, by increase in capital or by State aid. It is not without interest to note that France is at present in a position to carry out works of this magnitude. Attention has been drawn in the discussion to the type of overhead construction adopted and to the restrictions imposed in this country. There appear to be two methods which may be adopted in dealing with safety measures for a comparatively new and rapidly expanding industry: (1) To make the minimum or no regulations at the outset, and to make or add regulations as accidents or other causes point to their necessity. This, to some extent, was the way in which the Factory Acts were built up; and a heavy toll of life and limb was taken before the present, by no means perfect, rules and regulations were evolved. (2) The second method is to make stringent regulations at the outset, providing protection from every probable or, one might almost say, possible form of danger connected with the business, and to relax or modify these in the light of experience and, in the case of electric power distribution, improvement in the reliability of switching and other safety appliances. While it may be argued that this method imposes an unduly heavy burden on an infant industry, it certainly prevents the growth of vested interests in unsatisfactory and even dangerous methods, which are frequently most difficult and, generally, very costly to deal with. One finds an excellent object lesson in the lighting of passenger trains, where gas lighting is still retained. The decision as to whether the first or second method

shall be adopted appears largely to depend on the value placed on human life. Finally, it may be pertinent to remark that even in America it has been found necessary to adopt the slogan "Safety First."

Mr. W. D. Horsley (*communicated*): A very striking feature in connection with the paper is the great rapidity, extent and thoroughness of the recent developments of the Midi Railway. No comparison should be drawn with progress in this country. In France, and particularly on the Midi Railway, the conditions obtaining demand electrification. Coal costs probably four times as much as in England, and with the large amount of water power available an alternative to electric traction can hardly be considered. Other advantages such as higher average speeds, due to the overload capacity of the electric locomotive, and increased capacity of a given line for the same number of tracks, are common to all electrification schemes. It is of very great importance to hear of the adverse experience with regeneration on the Midi Railway. In view of the fact that this has always been claimed as one of the advantages of the electric locomotive, it would be of great value if the author would amplify his remarks concerning this point. What actual saving of energy has been obtained and what are the difficulties experienced? The author states that "the present programme is to establish around our mountain or seaside resorts a service of light and frequent trains." In the case of the former, at least, will not regeneration effect a large saving and compensate for any slight complication? With a regular and frequent service of trains in a hilly district it would perhaps be possible, with the line sections tied, to dispense with rotary machinery in the substations while still retaining regenerative braking. No interchange of energy would take place through the substations, but only through the line, the effect being simply to take less current from the supply. With regard to the mercury-arc rectifiers installed, it is not clear whether there are 12 phases or whether two 6-phase rectifiers are fed from a single transformer. The ripple in the d.c. voltage must be slight and, as stated in the paper, would not be likely to affect the operation of the motors; but it would be of interest to know whether any trouble has been experienced from this cause through interference with telephone lines. The Midi Railway has undoubtedly had a unique experience with electrification schemes and it would be of great value if the author would give some further comparisons of the single-phase and d.c. systems, particularly with regard to first cost, maintenance and overall efficiency.

Mr. A. Bachellery (*in reply*): There is no doubt that cheap electrical energy produced from water power is a very important factor in the development of railway electrification in France. Up to now, only suburban sections have been supplied with current generated by steam. The Paris–Orleans Company, however, proposes to use for its Paris–Vierzon line electrical energy obtained from the combustion of fuel and also from hydro-electric plants. All the power to be produced in the Midi Company's power stations will not be used for the railway, at any rate at first, and the company intends to sell its surplus electrical energy. This can be done only by permission of the Government. As I have mentioned, our experience both with 50-cycle rotary converters and with mercury-arc rectifiers has been quite successful. Practically no flashing-over occurs in our substations equipped with rotary converters. These machines include a cylindrical commutator but not, as Mr. Beaty believes, a radial commutator. We are to have, in a number of substations, English Electric rotary converters with radial commutators, but they are not yet in service.

Concerning the reasons why overhead collection has been chosen rather than third rail, there is not much to add to Mr. Dalziel's views on the subject. I may say, however, that we have a great many level crossings and, moreover, that on an existing railway it is often difficult—and would have been so in our case—to design a 1 500-volt third rail so as to leave the necessary clearance from permanent obstacles along the track and also from the rolling stock.

The synchronous condensers provided in the transformer substations not only are intended to improve the power factor, which is lowered by the industrial load, but are also necessary for the regulation of the voltage at the extremity of such long lines as ours. They can accordingly supply either leading or lagging wattless current.

The voltage-drop of 20 per cent is calculated from the substations. This is, however, not an average figure but a maximum one corresponding to a full-load train half-way between two substations. It is not, therefore, to be compared with the average loss of power calculated on other electrified systems.

Automatic switches to cut out a defective section are provided on the high-tension line as well as on the traction line. They are located in the substations. We have experienced no difficulties with the communication circuits due to interference from the 60 000-volt wires (which are fixed on the same supports as the contact line) except in the case of a short-circuit, which produces an inductive shock. The only precaution taken to prevent induction from our high-tension transport lines is the periodical transposition of the three-phase wires on their supports.

Voltage fluctuations in the direct-current wires, due to the use of mercury-arc rectifiers, give in the telephone a low musical note which does not prevent hearing. We prefer short track bonds to long ones because they are cheaper and less liable to be stolen. The difficulty was to find a type of short bond which would not be very quickly broken by the motion of the rail ends. The system which I have described seems to answer this purpose.

We have experienced no difficulty as regards restriction of free radial play of the bogies of our two-truck machines due to the couplings being fixed to the truck frames. On the contrary, in order to run such machines at a speed of 50 miles per hour, experience has led us to add to this restriction by putting in lateral buffers between the two trucks, where there was originally only a central coupling.

We have only one motor-generator set to feed the

auxiliary circuits on our locomotives. To have two such sets would certainly be safer, but also more expensive. My observation, however, did not allude to this, but to the fact that to drive the various auxiliary apparatus by special 1 500-volt motors instead of by low-tension motors would be a mistake, small 1 500-volt motors being very liable to get out of order. It is, in fact, because this motor-generator has to supply all the auxiliary motors on the locomotive, including the air-compressor, and also to excite the traction motors when regenerating and to provide the lighting of the train in some cases, that it has to be capable of an output of 72 kW. The 600-ton load on which we based the study of the 4–8–4 locomotive is not, as Mr. Beaty thinks, a test load, but a practical load which has already been attained quite frequently by our steam-driven express trains.

In reply to Sir James Aspinall's question concerning regenerative braking, we think that electric braking is necessary on lines where there are steep gradients; but we prefer rheostatic braking to regeneration because it is more easily managed by the driver on account of the voltage factor being eliminated.

Current supplied from the locomotive will only be used for carriage lighting on branch lines, and in such cases no batteries will be provided. On the main lines, the current for lighting the carriages is supplied at 25 volts from a dynamo on each coach, and the lighting couplings on the locomotive will not be used.

With reference to the table in Mr. Stevens's communication, only passenger trains are referred to, local and freight trains being omitted. The speeds tabulated are scheduled speeds and include intermediate stops, whilst the details regarding the number of stops do not refer to the fastest trains. For instance, on the Bordeaux–Hendaye line, the Southern Express and the Pyrenees–Cote d'Argent Express have only one intermediate stop on the 92-mile trip from Bordeaux to Dax, and only 5 in all. The scheduled speed of the former is 41 miles per hour on the down journey and 40 miles per hour up, and it is 51 miles per hour between Bordeaux and Dax. Similar remarks could be made as regards the express trains between Pau, Montréjeau and Toulouse. Accordingly, the figures in the table do not always give an accurate idea of the lines to which they refer.

PHONOFILMS, OR TALKING PICTURES.

By C. F. ELWELL, Member.

(ABSTRACT *of a paper read before the* LONDON STUDENTS' SECTION, 16*th November*, 1923.)

Attempts to record sound vibrations photographically are not new. The first successful attempts to record sound upon a cinematograph film were those of Ruhmer, who in 1906 and 1907 succeeded in obtaining a crude photographic record of telephonic currents which were superimposed upon the direct current flowing through what was known as the speaking arc. These telephonic currents produced sufficiently large fluctuations in the light from the arc to make it possible to record them photographically upon a film moving at several metres per second.

Properly-synchronized talking-motion-pictures involve light photography at 186 000 miles per second and sound photography at 1 090 feet per second. In addition, if results are to be good, it is necessary to record frequencies of from 600 to 2 000 for voices and good articulation, and from 27 to over 4 000 for music. If the talking-motion-picture is to be practical and commercial it is necessary to put the sound and picture records on the same film, which should be the standard film employed in thousands of cinemas. Dr. de Forest has solved the problem by recording the sound in the blank space, about 2 mm wide, usually left between the driving holes in the film and the picture. It is instructive to watch this band when the talking-motion-pictures are being shown, and to note the change in the number and thickness of the horizontal lines as the frequency of the sound varies. It will be noticed that the synchronization is absolute, and that the width or amplitude does not vary, the sounds being reproduced by the variations in the density of the photographic image on the film.

The photographs are taken by means of a standard motion-picture camera to which is fitted the necessary apparatus for recording the sound.

The ideal form of transmitter for distortionless work is one without a diaphragm. Various forms of transmitters without a diaphragm are now available, e.g. the flame transmitter, consisting of a gas flame in the form of a bat-wing, which is made more conductive by means of salts and in which two platinum electrodes are suitably inserted. Sound waves impinging upon the flame alter its conductivity and cause a current of varying intensity in a local circuit.

Another form of transmitter having no diaphragm and employing very fine and very short platinum wires has been tried. The wires are heated to a dull red by means of a local source of current, and when sound

waves impinge upon these wires their resistance increases or decreases. By means of a local battery and a telephone transformer a faithful representation of the sound waves is obtained with frequencies as high as 3 000. The sensitiveness of the device is greatly increased by means of a gentle stream of air. To be really useful, such a transmitter should be capable of faithfully transforming into electric currents sound waves emitted at distances of from 5 to 25 ft. The resulting currents are naturally exceedingly small.

The method successfully adopted by Dr. de Forest is to pass the amplified telephonic currents through a gas-filled two-electrode valve, which he calls the "photion." The photion glows at all times with a violet light of high actinic quality, and the intensity of this light increases or decreases in exact correspondence with the fluctuations of the amplified telephonic currents. The photion lamp is mounted in the motion-picture camera at a point where the film is moving continuously, that is some 10 inches away from the window of the camera, at which point the motion of the films is intermittent for the purpose of photographing the picture. The light from the end of the "photion" lamp is focused by means of a lens upon a very fine slit directly in front of the emulsion side of the film. This slit, in order that the highest harmonics may be recorded upon a film travelling at a speed of from 12 to 18 inches per second, must not be more than two-thousandths of an inch in width. The length of the slit is about $\frac{3}{32}$ inch.

In order to reproduce the sounds recorded upon the film, a tubular-shaped attachment is fastened just below the film magazine of a standard motion-picture projector. This attachment contains a small incandescent lamp, which shines through a lens and then through a slit two-thousandths of an inch in width and $\frac{3}{32}$ inch in length. This slit is so located that the sound record upon the film passes directly in front of it, and thus the intense light from the small incandescent lamp passes through this cloudy band.

The light which passes through the film falls upon a photo-electric cell. The cell which has been adopted by Dr. de Forest is that invented by Mr. T. W. Case, and known as the "thalofide" cell. The thalofide material is composed of thallium, oxygen and sulphur, which is fused on a $\frac{3}{4}$-inch diameter quartz disc. This disc is mounted in a glass bulb, which is then evacuated in order to prevent oxidation, and also to increase the sensitivity of the photo-active material. The resistance in the dark is high compared with the ordinary selenium cell, and may range from 5 megohms to 500 megohms. The average sensitivity is such that the direct resistance is lowered by 50 per cent when 0·25 ft.-candles from a tungsten-filament source falls upon the photo-active material. It is without appreciable lag. Probably the best-known material for photo-electric cells is selenium, but its lag in response, or fatigue, bars it from talking-motion-picture work. The variations in the amount of light caused by the presence of the dense and thin horizontal lines on the film between the incandescent lamp and the photo-electric cell, are thus transformed into electric currents, which are quite small, being of the order of a weak wireless signal. These small currents are next amplified by means of a four- or five-stage amplifier, which must also be distortionless, and the amplified current is then passed through one or more loud-speakers, completing the cycle by transforming electric currents into sound.

Although loud-speakers have been developed to a high state of perfection, they still leave much to be desired. I do not believe that perfection will come as long as a diaphragm is used. Some better method of transforming electricity into sound waves is required, and here is a field for the ingenuity of Students, as the experimental apparatus necessary may be quite inexpensive. The reverse action, for example, of the batwing type of flame transmitter is susceptible of development; also that well-known possibility of influencing a singing arc may yet be used. When one milliampere can be made to influence a 10-ampere direct-current arc, it is still possible that a workable method may be evolved in which an arc is employed.

THE CHARACTERISTICS OF A D.C. SERIES MACHINE SELF-EXCITED BY RECTIFIED CURRENT FOR PURPOSES OF REGENERATIVE CONTROL.*

By R. D. ARCHIBALD, D.Sc., Member.

(*Paper first received* 13*th July, and in final form* 16*th November,* 1923.)

SUMMARY.

The present position of regenerative control for tramcars is discussed, and a description is given of a method of self-exciting the field of a series motor with a low-voltage rectified current transformed from alternating-current tappings in the armature. Under these conditions the motor behaves like a shunt machine, and characteristics are shown when it is acting regeneratively and also when it is used as a generator and motor.

Calculations are given for finding the conditions of sparkless commutation of the rectifier, and tests are included which corroborate the calculations.

In conclusion, some points are discussed with regard to the practical application of the device.

The position of regenerative braking at the present time is that whilst it has been successfully applied to railway systems, and is almost essential for mountain railways, it has found small favour with those in charge of tramway systems, even in places where the hilly nature of the country would appear to justify the assumption that its use would lead to economy. Numerous systems have been proposed for tramway use, and some of these have been tried and proved workable, but the additional outlay and complication have been too great for the advantage gained; consequently the power used in accelerating and in ascending gradients is still very largely wasted. It has often been deplored that no simple device for recovering this energy in the case of tramcars has so far been produced. Yet there are many towns with gradients of sufficient length and steepness where the saving in energy and in wear and tear of brakes would be a real one, provided that the accessory apparatus required were not too costly, even if the power lost in starting and stopping had to be sacrificed.

Whilst working with a rectifier for improving the balance of a three-wire d.c. system (see *Journal I.E.E.*, 1922, vol. 60, p. 303) the author thought that some advantage might be gained by making a series motor self-exciting with a low-voltage rectified current transformed from alternating-current tappings in the armature. This method of excitation has been adopted for alternators in the past, though mainly for purposes of compounding, but it has been abandoned in favour of more effective controls such as the Tirrill regulator and others, and a common impression exists that the chief objection to it was due to sparking of the rectifier. Miles Walker, however, has shown in a paper on "Compensated Alternate Current Generators"* that a rectifier could be quite satisfactorily employed for this purpose without sparking.

In the case of the series motor a potential transformer is used to reduce the voltage at the armature tappings to the pressure required for exciting the field. Thus the problem of sparking differs slightly from that in the case of the alternator, but it will be seen from the tests which follow, and from the investigation into the question of commutation by the rectifier, that sparking is not likely to be a source of trouble in the case of the series motor—possibly less likely than in the case of the alternator. The advantages of exciting a series motor in this way, over excitation by a direct-current exciter, are:—

(1) For the same volt-ampere output the cost of a static transformer is considerably less than that of a rotating machine, provided that the frequency of the alternating current is not abnormally low. The extra cost of the rectifier is not a heavy item.

(2) The transformer can be more readily stowed than a rotating machine.

(3) The driving of the rectifier from the axle or spur wheel of the motor is easier to arrange than an exciter, as the rectifier is small. The rectifier could more easily be detached for inspection.

(4) The power used in driving the rectifier is small.

To set against these, there is the necessity of tapping the armature (of one or both motors) for the alternating current, and the provision of slip-rings and brushes. There is difficulty in doing this on account of the cramped space available, but the current is only a matter of a few amperes, so that not much space is required. The method employed for these tests is not suitable for a traction motor, but numerous other ways suggest themselves and the problem does not present insuperable difficulties. Any method adopted must be such that it can be applied to an existing traction motor without danger of breakdown and at a trifling cost.

The tests were made with the apparatus available in the electrical laboratories at the Technical College, Dundee. The series motor used was a 4-pole machine with a normal output of 8 h.p. at 770 r.p.m. on a 400-volt circuit. The armature was wave-wound with 4 brush spindles. The commutator had 153 segments, and tappings were taken from No. 1 and No. 39.

The motor was driven as a generator by a similar

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

* *Journal I.E.E.*, 1905, vol. 34, p. 402.

motor mounted upon the same bedplate and separately excited from a battery. The field-magnet system of the driving motor was mounted on ball bearings and was arranged for measuring the torque by the reaction on the frame. The arrangement could be used for measuring the torque exerted on, or by, either machine.

The connections for the test are shown in Fig. 1. The armature of the motor (M_1) is tapped at the points 1, 1′ which are connected to the slip-rings (2, 2′). The slip-ring brushes (3, 3′) are connected to the primary of the transformer (T). The secondary of T is connected to the brushes (4, 4′) of the rectifier (R). These brushes

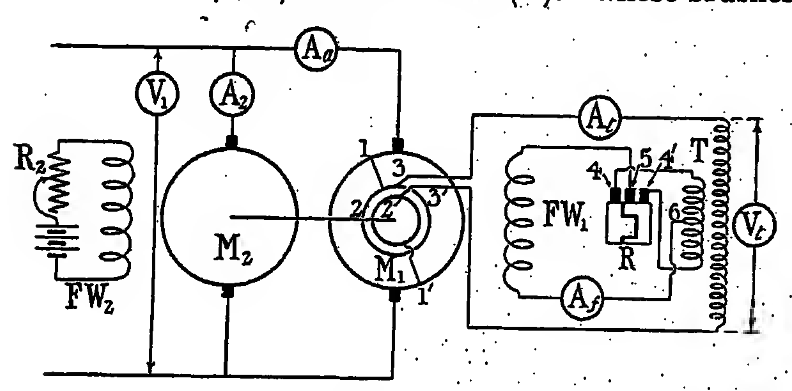


Fig. 1.

make continuous contact with the two parts of the commutator as shown. The centre brush (5) makes contact with 4 and 4′ alternately as the commutator revolves. The secondary winding of T is tapped at the centre point (6). Unidirectional current is then obtained between brush 5 and tapping 6, and these are connected to the field winding (FW_1). The driving motor (M_2) was run off the same supply and its field winding (FW_2) was excited from a battery through a variable resistance (R_2). Voltmeters were placed at V_1 to read the line volts, and at V_T to read the transformer primary voltage. Ammeters were placed at A_2,

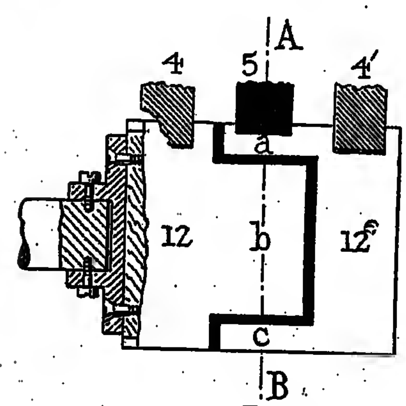


Fig. 2.

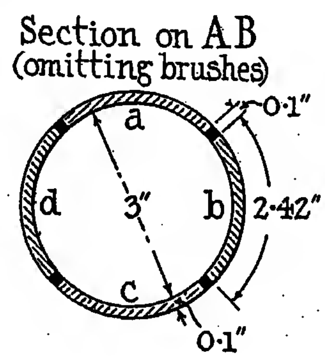


Fig. 3.

A_a, A_t and A_f, to read the armature current of M_2, the armature current of M_1, the primary current of T, and the field current of M_1, respectively.

The transformer (T) had a normal output of 6 kW at 50 cycles and a voltage ratio of 440/245.

The windings were tapped at points giving the following voltages:—

High tension: 192, 29, 162, 29, 29
Low tension: 106, 16·5, 89·5, 16·5, 16·5.

The rectifier was fixed on the commutator end of the shaft in the manner shown in Fig. 2. The commutator was made from a short length of 3-in. copper pipe, 0·1 in. thick, fixed on a hardwood core. A zigzag slot about 0·1 in. wide was cut round the pipe forming the 4 segments (a, b, c, d) and the two parts (12 and 12′). Brushes 4, 4′ were of copper gauze, and brush 5 of hard-quality carbon ("link C4") ½ in. wide by ⅜ in. broad. The current density in brush 5 at full load (17·5 amperes) was thus 47 amperes per sq. in.

Characteristics as a Regenerator.

The regenerative properties of the arrangement were tried by a series of tests with different ratios of transformation. At each ratio a number of readings were obtained of: (1) current regenerated, (2) torque, (3) speed.

The order of procedure was, in general, as follows:—

The field switch of the driving motor (M_2 in Fig. 1) was closed and the motor was run up to speed through a starting resistance. Usually the machine M_1 then built up its field like a shunt generator. When, at high ratios of transformation, it did not do so automatically, it was sufficient to pass a current through the armature from the mains with a resistance in series. This forced a current through the transformer primary and field. In this way the contact resistance of the rectifier brushes was sufficiently reduced to enable the field to build up. The motor could then be disconnected from the mains without losing its field (unless, of course, the ratio of transformation used was above a critical point). The speed was then adjusted by varying the field of the driving motor until the voltage of the regenerator was the same as that of the supply, when the main switch of the regenerator was closed. The set now acted like two shunt machines run back to back, and by weakening the field of M_2 the speed could be raised and M_1 caused to regenerate.

The brushes of the rectifier were set in such a position that the rectifier segments were just being short-circuited when the position of the armature tappings was half-way between the positive and negative brushes. In other words, brush 5 was in advance of the geometrical neutral axis of the rectifier by a distance $\frac{\text{One brush width} - \text{one mica width}}{2}$. This position gave sparkless running throughout.

In addition to the readings of voltage (V_1), torque, speed and regenerated current (A_a), readings were taken of the field current of the driving motor and of the regenerator (A_f), the slip-ring voltage (V_t), the primary current of the transformer (A_t), and the armature current (A_2) of the driving motor.

Tests were taken with the supply pressure equal to half the normal and also at full voltage, thus representing the case of the motor running respectively in series or in parallel with another. With the arrangement of the tappings in the transformer, however, it was possible to obtain a larger range of ratios of transformation at the lower voltage, and the tests taken at half voltage will therefore be studied in detail first.

The tests A, B, C and D were taken with the two

adjacent 29-volt portions of the high-tension winding used as the secondary of the transformer, the tapping between them forming the tapping 6 in Fig. 1. In the tests E, F and G, the portions used were the 16·5-volt sections of the low-tension winding.

The variations of torque and speed with current regenerated are plotted for all the tests in Fig. 4. A study of these curves will show that the characteristics are similar to those of a shunt machine. A given ratio of transformation corresponds to a given setting of the field resistance in a shunt machine. For a given ratio, the torque is practically proportional to the armature current, the slight bend in the torque curve being due to the weakening of the field by armature reaction. The field current remained practically constant with load, though the tests showed a slight rise of field current with load at the higher ratios, which gave a small compounding effect. (In test G the field current rose from 8·2 amperes at no load, to 9·3 amperes with a load of 15 amperes.) For all practical purposes, however, the arrangement behaves like a dynamo with constant field on a constant-voltage circuit, and greater loading is brought about by a rise in speed. With low ratios, the field is strong, the torque large, and the speed low, and the rise in speed from no load to full load is a matter of some 15 to 20 per cent. With high ratios, on the other hand, the percentage rise in speed is much greater, since armature reaction still further weakens the field. For example, in test G the rise in speed from zero to 17·5 amperes is from 710 to 990 r.p.m., or 40 per cent.

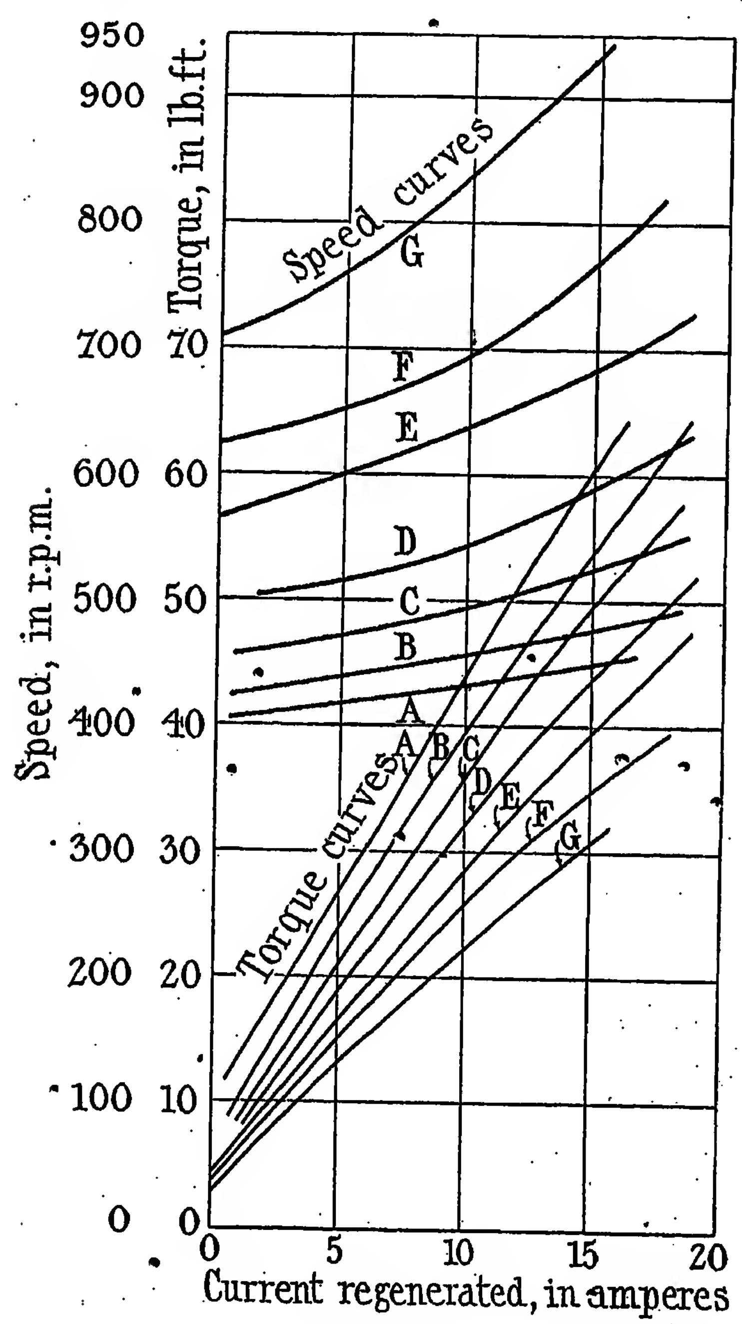


Fig. 4.

Speed/torque curves are plotted in Fig. 5, with speed as ordinates and torque as abscissæ. On each of these curves points can be found corresponding to some definite value of the load current, from the curves in Fig. 4. Such points are shown in each case for 2·5, 5, 7·5, 10, 12·5, 15 and 17·5 amperes. Constant-current curves can then be drawn as indicated by the dotted lines. In this form * a better idea of the relation between braking effect, speed and current regenerated is obtained. If the gear ratio and the diameter of the wheels on the track are known, the ordinates can be made to represent speed in miles per hour, and the abscissæ braking effort at the track.

The effect of a change of ratio can now be seen. For example, suppose that the gradient, and therefore the torque, are constant and that the machine is running at the point x (Fig. 5), so that the torque is 30·5 lb. ft., speed 730 r.p.m., and current regenerated 12·5 amperes, the ratio being 24·2/1. On suddenly changing the ratio to 26·7/1, the current and braking effort would alter along a horizontal line from x to the point y on the curve G, the speed being momentarily constant.

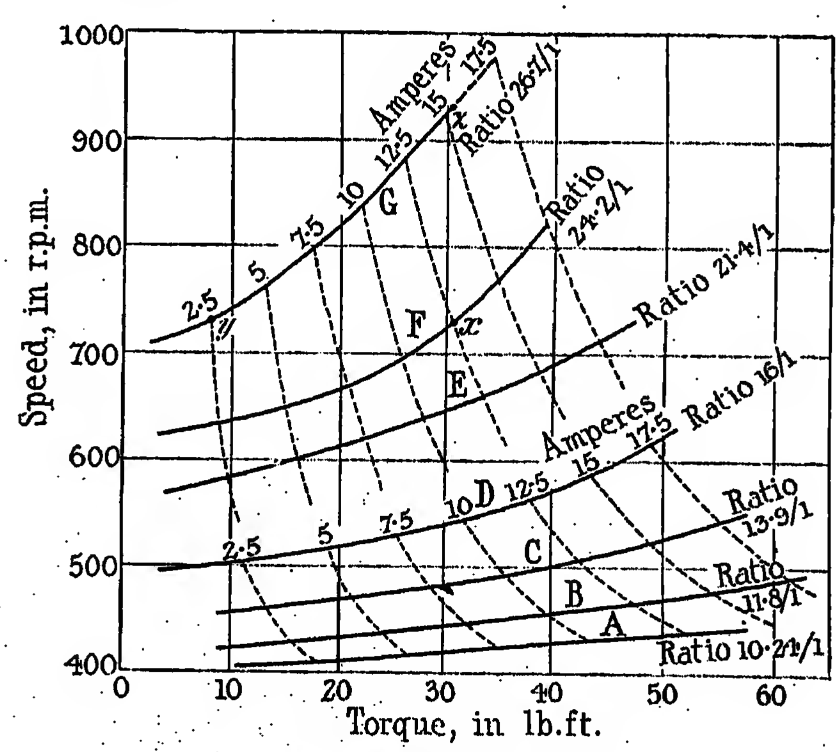


Fig. 5.—Speed/torque curves.

The current and torque (or braking effort) being now very much reduced, the speed rises along the curve G until the torque is the same as before at point z. The regenerated current is now 15·2 amperes, and the speed 930 r.p.m.

It might be mentioned here that the field current

* Fairburn and Harper: "Analysis of Regenerative Braking," *English Electric Journal*, vol. 2, no. 7.

could be varied equally well by the use of a variable resistance in the primary circuit of the transformer without involving much loss, since the current is small. This would be analogous to the use of the field-regulating resistance in a shunt machine. The transformer would then only require to be designed for the lowest ratio, and the higher speeds would be obtained by inserting resistance. Thus a smaller transformer could be used, at the expense of the losses in, and cost of, the resistance.

The compounding effect noticeable at the higher speeds is caused by the gradual increase in voltage at the slip-rings as the load on the d.c. side increases. This raises the secondary voltage of the transformer and rectifier, and hence the field current.

This rise in slip-ring voltage constitutes a change in the ratio of a.c. to d.c. voltage in the armature, and is attributable to the distortion of the field caused by the load current on the d.c. side.

In case any reflex action from the rectifier might be a disturbing factor in the wave-shape of the slip-

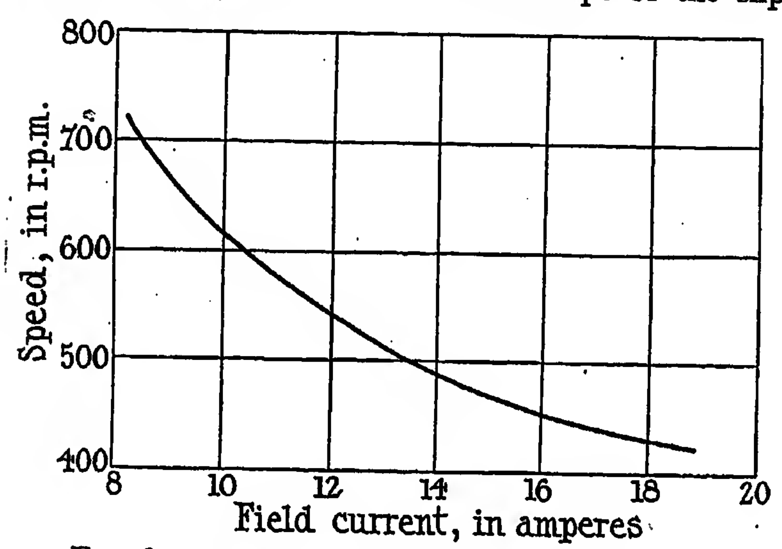


FIG. 6.—Speed at no load, with varying field.

ring voltage, tests were made with the rectifier connected to a separate inductive resistance, the field magnets being excited from a battery. The brush position of the rectifier was the same as that used in the previous tests, and no effect was produced on the slip-ring voltage by switching on and off the rectified current, nor did switching off the transformer primary make any difference.

Besides the increase in the slip-ring voltage with load, another factor which affects the compounding is the position of brush 5. This, however, will be discussed later.

FACTORS DETERMINING THE SPEED.

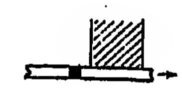
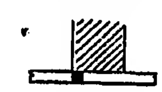
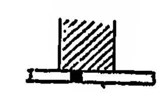
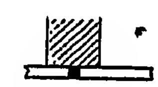
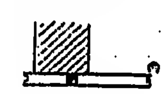
The speed is a function of the internal voltage, E, of the armature, and the flux per pole.

If V = terminal voltage,
I_a = armature current,
R_a = resistance of armature and brushes,
then $E = V + I_a R_a$.

The flux depends on the field current and on the effect of armature reaction. The brushes of the armature were set in the neutral position during the tests, so that the armature reaction consisted of cross-magnetizing ampere-turns only. With constant terminal voltage the cross ampere-turns combine to raise the speed in two ways: (1) by the demagnetizing effect due to distortion of the field; and (2) by shifting the magnetic neutral position ahead of the geometric position so that the brushes, which remain in the latter position, are not in the proper place for giving maximum voltage. This second effect is difficult to estimate and is small.

The first factor, however, has an appreciable effect, and can be approximately determined from the design particulars of the machine. From a knowledge of this and the resistance R_a, and also a curve representing speed plotted against field current at no load, it is possible to show roughly how far the speed might be

TABLE 1.

Armature: Terminal P.D.	Armature: Current	Field current	Speed	Brush position	
volts	amps.	amps.	r.p.m.		
212	0	10	610	1	
212	18	13	640		
212	0	11·2	560	2	
212	18	12·7	640		
212	0	11·6	545	3	
212	18	12·7	650		
215	0	11·4	555	4	
214	18	11·8	700		
215	0	11·4	560	5	
214	18	11·2	760		
210	0	10·9	565	6	
210	16*	9·7	830		

* Unstable with greater armature current.

expected to rise with load, and to compare the results of the calculation with those found on test.

The variation of speed with field at no load was tested: (1) with the field excited by the rectifier, and (2) with the field separately excited, the rectifier and transformer being disconnected. Practically the same result was obtained in both cases, and the curve is plotted in Fig. 6. The speed/load characteristic calculated from this curve did not, however, agree with the tests in Fig. 4, and it was found that the characteristic was affected considerably by a small movement of brush 5 of the rectifier. Tests were therefore made of the alteration in speed from no load to full load with different brush positions. The ratio used was the same as in test E and the results are shown in Table 1. In fixing the position of the brush, in each case the tappings were set midway between the positive and negative brushes, which were

in the neutral axis. The brush was then set relatively to the mica, as shown in the table.

With the brush in advance of the mica by the distance of 2 mica widths, the machine would not excite properly and was apt to excite in the reverse direction, but only partially. Quite satisfactory running was obtained in positions 1, 2, 3, 4 and 5, but in position 6 there were again signs of instability. It will be noticed that the speed-range increases as the brush is moved back, or the compounding effect becomes greater as the brush is moved forwards. This is due to the forward movement of the main field under the pole with load. It will be clear that if brush 5 is set so that at no load the E.M.F. is rectified at zero point, then, as the load comes on, the centre of the field moves forward and rectification will take place before the E.M.F. has reached zero. The rectified E.M.F. will therefore be reduced. But if the brush is forward of this position, then at no load the E.M.F. will have reversed before rectification takes place, and the rectified E.M.F. will therefore be less than before; as load comes on and the point of zero E.M.F. moves forward, the rectified E.M.F. increases.

of tappings on the transformer. The position of brush 5 was the same as in the tests on half voltage (see page 234) and the machine self-excited without any aid in both

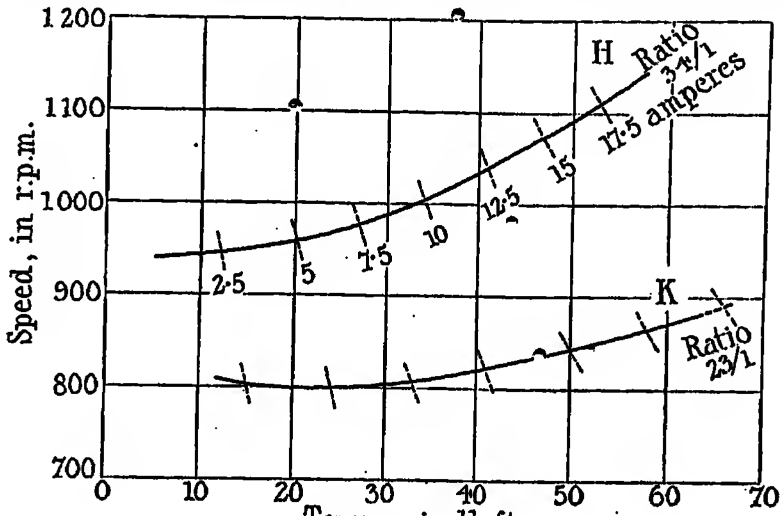


FIG. 7.

tests. Curves of speed are plotted against torque in Fig. 7, and constant-current lines are indicated similarly to those in Fig. 5.

TABLE 2.

Regenerator			Transformer primary		Speed	Ratio, d.c./a.c. voltage
Terminal P.D.	Current					
	Armature	Field	P.D.	Current		
volts	amps.	amps.	volts	amps.	r.p.m.	
400	0	19·2	286	1·35	790	1·4
392	3·6	18·9	280	1·3	Constant	1·4
383	6·6	18·4	274	1·21		1·4
373	8·4	18·1	270	1·15		1·38
358	11	17·6	262	1·09		1·36
348	13	17·3	258	1·05		1·35
332	16	16·7	250	1·0		1·33
314	18·5	16	244	0·915		1·29
300	21·2	15·5	242	0·86		1·24
280	23	14·7	234	0·8		1·19
256	24	13·8	218	0·72		1·17
228	26	12·8	214	0·65		1·06
214	27	11·9	210	0·6		1·02
160	29	9·0	190	0·5		0·84
180	28	10·2	—	—		—
128	29	7·8	—	—		—

Ratio = 23·15, viz. (191 + 29 + 162)/16·5.

On the other hand, if the brush is in a backward position the E.M.F. at no load will be less, but on load it will be still less.

CHARACTERISTICS AS A REGENERATOR ON FULL VOLTAGE.

Connections were made as in Fig. 1 and the supply was taken from the 400-volt mains. Two different ratios of transformation were used—the first, 23·15/1, which was the lowest possible, and the second, 34·1/1, which was the highest possible with the arrangement

VOLT-AMPERE CHARACTERISTIC AS A GENERATOR AT CONSTANT SPEED.

The volt-ampere characteristic as a generator is interesting, in showing the resemblance to that of a shunt machine. Connections were made as in Fig. 1, with the exception that M_1 was connected to a lamp load instead of to the line. The ratio used in the transformer was 23·15/1, the primary consisting of the portions 191, 29 and 162, and the secondary of the two portions 16·5 with a tapping between them.

This ratio gave with no load 400 volts at 790 r.p.m., or nearly normal full-load speed.

The armature brushes were set in the neutral position, and the rectifier brush (5) was given the same amount of lead as before. The speed was maintained constant at 790 r.p.m. and the machine was loaded to the limit of its output, which occurred at about 29 amperes. Readings were taken as shown in Table 2. From these the external and internal characteristics have been plotted in Fig. 8.

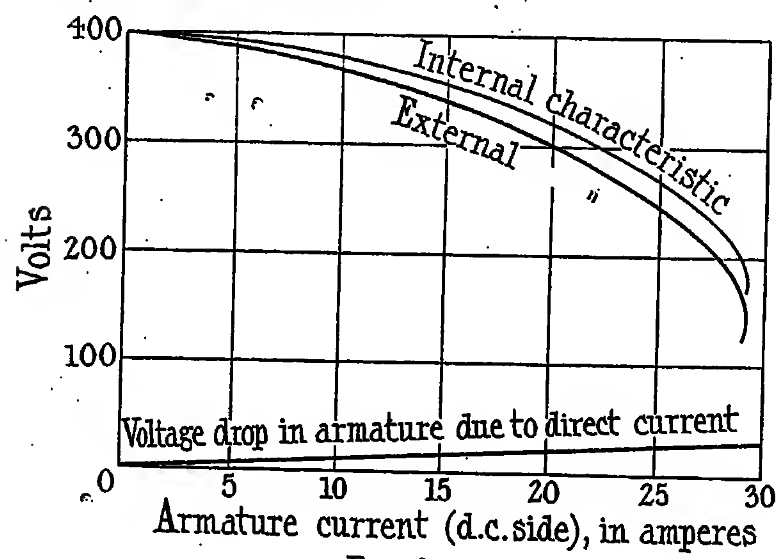


FIG. 8.

It will be seen that the characteristics are those of a shunt-wound generator in all respects. The voltage falls away due to the drop in resistance in the armature and also to armature reaction on the field, and a point of maximum current is reached. Near this point the readings were very uncertain, and a considerable difference could be made by varying the pressure on brush 5. By increasing the pressure a point at 38 amperes, 120 volts, was obtained.

A point of interest is the relation between the d.c. and a.c. voltages of the armature. At no load the ratio, d.c./a.c. voltage, was 1·4, or approximately $\sqrt{2}$. At 18·5 amperes it fell to 1·29, and at 27 amperes to 1·02. The last three readings are not reliable owing to unsteady conditions, so that the ratio 0·84, which makes the a.c. voltage greater than the d.c., may be wrong, though not necessarily impossible.

TABLE 3.

Rectifier brush position	P.D.	Current		Speed
		Arm.	Field	
	volts	amps.	amps.	r.p.m.
Neutral ..	424	0	21·9	800
	366·4	17·5	18·9	800
Back * ..	391	0	17·9	800
	246	8	9·5	800
Forward † ..	422	0	21·4	800
	380	17·5	20·5	800

* Inverse of position 3 (Table 1). † Same as position 3 (Table 1).

The characteristic is affected considerably by a small movement of the rectifier brush 5. Tests were taken of the drop of voltage from no load to full load when brush 5 was at the neutral position, behind the neutral position, and in front of the neutral position. The results are shown in Table 3. With the brush

TABLE 4.

MOTOR M_1.

Terminal P.D.	Current		Torque	Speed	Input	Output	Efficiency
	Armature	Field					
volts	amps.	amps.	lb. ft.	r.p.m.	kW	b.h.p.	per cent
418	1·73	20·2	1·06	810	0·725	0·164	16·9
419	2·17	20	2·93	810	0·91	0·45	36·9
422	3·85	20·6	8·5	810	1·62	1·31	60·5
418	5·75	20·4	15·2	795	2·41	2·31	71·3
416	7·85	20·2	23·3	790	3·26	3·52	80·5
418	10·6	20·1	33·2	790	4·43	5·0	84·2
418	13·1	19·8	41·5	—	—	—	—
420	13·1	19·6	42	800	5·5	6·42	87
422	14·85	19·5	48·3	800	6·27	7·38	87·7
422	17·85	19·5	57	800	7·52	8·72	86·5
423	19·6	10·5	63	810	8·3	9·73	87·3
LIGHT READINGS WITH M_2 AS MOTOR.							
420	(M_2) 1·12	0	—	810	(M_2) 0·47	—	—
416	2·27	19·5	—	805	0·945	—	—

Ratio = 23·25.

lagging, the maximum current that could be obtained was only 8 amperes, the drop in voltage being nearly 40 per cent. With further forward setting the regulation improves within the zone of sparkless commutation.

Characteristics as a Motor on Constant Voltage.

Connections were made as in Fig. 1, the direction of rotation being reversed so that the torque transmitted from M_1 to M_2, which now acted as a generator, was in the same direction as before. This saved any alteration of the torque-measuring device.

Tests were made with the brush 5 in the same forward position as before. No sparking at the rectifier was observed up to full load, but there were signs of instability, and at an overload of about 15 or 20 per cent the rectifier developed violent sparking, the speed commenced to rise, and the cut-out operated. Brush 5 was then set at the neutral position and the tests in Table 4 were taken. The maximum load which the spring balance would read was equivalent to 9·73 b.h.p., but a much greater load could be applied without the machine being unstable.

For the purpose of comparison, light readings were taken of M_1 with rectified field current, and of M_2 with separate excitation of the same value. With no load current in the generator M_2 and no current in the field, the input to M_1 was 725 watts, as shown in the first set of readings in Table 4. The output was 122 watts. This is the loss due to friction and windage in M_2. The two machines being similar, we may take it as being the friction and windage loss in M_1 also. To this has to be added the friction loss in the rectifier. The total pressure on brush 5 was 3 lb. Making a small allowance for loss in the gauze brushes, we may assume the friction loss in the rectifier to be about 16 watts.

The resistance of the rectifier and field circuit was 0·59 ohm. The loss is therefore $(20 \cdot 2)^2 \times 0 \cdot 59$, i.e. 240 watts. We may now deduce the other losses from the total light-load losses on test as follows :—

etc. Output, torque, efficiency and speed curves are plotted with armature current as abscissæ in Fig. 9.

Tests of the effect of the position of brush 5 on the speed characteristic were made and are given in Table 5. As would be expected, the compounding effect gets greater as the brush is moved backwards, since the

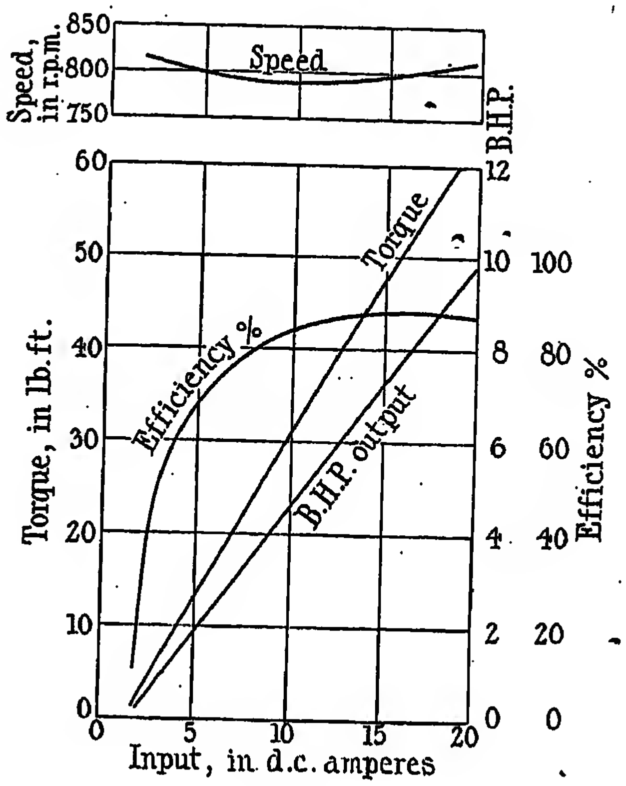


FIG. 9.

armature current and distortion are in the reverse direction from that in a generator. This is shown by the greater drop in speed from no load to full load as the brush is shifted backwards.

Conditions Necessary for Sparkless Commutation of the Rectifier.

The problem of the commutation of single-phase rectifiers has been investigated by Prof. Miles Walker in connection with compensated alternating-current

	M_2 watts	M_1 watts	Remarks
Friction and windage	122	122	Lost in M_2
	138	138	Lost in M_1 + rectifier
Copper loss in field circuit ..	—	240	
Iron loss (to balance)	210	Iron loss and loss in transformer (to balance) 225	
Total from test in Table 4 ..	470	725	

At 440 volts across the whole high-tension winding, and 50 cycles per second, the transformer loss was 107 watts at no load. In this case the frequency is nearly half normal and the voltage at least 20 per cent below normal. The losses will therefore be of the order of about 20 to 30 watts, including the small copper loss. We may presume from the above figures that the rectified current in the field does not introduce any appreciable extraneous losses due to eddy currents,

generators (*Journal I.E.E.*, vol. 34) where the method of compensation used was a rectified current, proportional to the main current, passed through a portion of the field winding. The results showed that sparkless commutation could be obtained at all loads with a fixed brush position, provided that the power factor did not alter.

The problem in the case of the series motor differs from that of a compensated alternator in several respects.

In the first place, a potential transformer is used and, as the primary is placed across the whole armature winding, the short-circuit must necessarily last a short period, at or near the point of no voltage. In the case of the alternator a small short-circuit period causes much greater fluctuation in the value of the current in the compensating winding. The compensating winding is, however, only a portion of the field winding,

TABLE 5.

Brush position	P.D.	Current		Speed
		Arm.	Field	
	volts	amps.	amps.	r.p.m.
Neutral	422	2·1	21·3	800
	422	17·5	21·3	780
Back *	422	2·2	20·9	810
	422	17·5	21·2	782
Forward † ..	422	2·1	21·2	800
	422	17·5	20·8	790

* Inverse of position 3 (Table 1). † Same as position 3 (Table 1).

whereas in the series motor the whole field winding is used. Thus the variation of current is considerably reduced by the high inductance of the field.

In order to determine whether there was an appreciable variation of current in the field due to the pulsating nature of the voltage of the rectifier, an induction-type ammeter was placed in the field circuit. No movement of the pointer could be detected on switching on or off the field circuit. With the field separately excited and

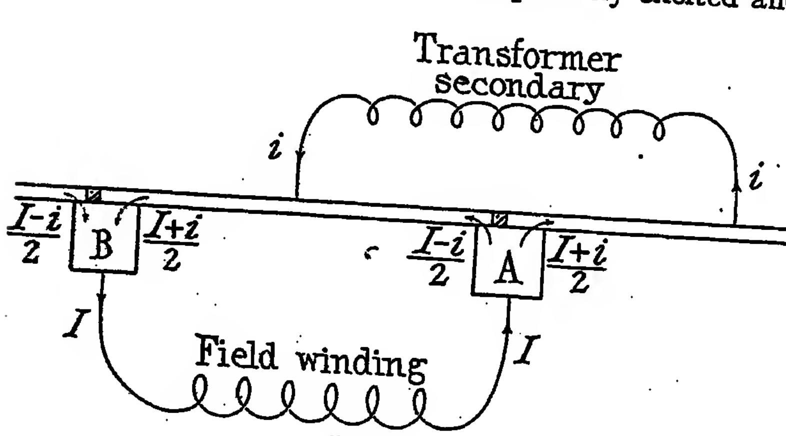


FIG. 10.

the rectifier connected to a non-inductive circuit consisting of a carbon-block resistance, a considerable deflection of the induction ammeter was shown with 15 amperes registered on a moving-coil instrument in series with it. It can be presumed from this that the inductance of the field winding was sufficient to keep the rectified current nearly steady. For practical purposes, therefore, the assumption that the rectified current remains constant is justifiable.

In the first place, a rectifier with two brushes on the commutator will be considered, as in Fig. 10, which shows a two-segment commutator developed out straight.

Let I = the current (assumed constant) in the field winding;
T = time of short-circuit in seconds;
t = time from commencement of short-circuit in seconds;
i = short-circuit current in secondary of transformer at time t;
R = resistance of a single total brush contact;
r_1 = contact resistance between brush and arriving segment;
r_2 = contact resistance between brush and leaving segment;
L = total equivalent inductance of transformer secondary.

Since i varies very rapidly, we may take it that r_1 and r_2 do not vary with the current density, so that

$$r_1 = R\frac{T}{t} \quad \text{and} \quad r_2 = \frac{RT}{T-t}$$

The currents I and i will be distributed as shown in Fig. 10. Consider the circuit commencing from brush A passing through the transformer secondary and back to A in an anti-clockwise direction.

By Kirchhoff's second law we have

$$\frac{I+i}{2}r_2 - \frac{I-i}{2}r_1 + L\frac{di}{dt} = 0 \,*$$

or

$$\frac{RT}{2}\left(\frac{I+i}{T-t} - \frac{I-i}{t}\right) + L\frac{di}{dt} = 0$$

$$\frac{di}{dt} = -\frac{RT}{2L}\left(\frac{I+i}{T-t} - \frac{I-i}{t}\right)$$

The conditions for sparkless commutation are that the constant $RT/(2L)$ is greater than unity, or

$$R > \frac{2L}{T} \quad \therefore IR > \frac{2IL}{T}$$

Now the average reactance voltage induced in the transformer secondary is $2IL/T$, and therefore

$\frac{2IL}{T}$ must be less than IR

The reactance voltage must therefore be less than the voltage-drop at one brush contact.

In the case of the single-brush rectifier (Fig. 11) it simplifies matters to choose $2I$ as the value of the current in the field winding, and, as before, the value of the short-circuit current in the transformer secondary † varying between the limits $+I$ and $-I$. The distribution of the currents during short-circuit is then as shown in the figure.

Using the same symbols as before and going round the path of short-circuit current in an anti-clockwise direction, we have

$$\frac{(I+i)RT}{T-t} - \frac{(I-i)RT}{t} + L\frac{di}{dt} = 0$$

$$\therefore \frac{di}{dt} = -\frac{RT}{L}\left(\frac{I+i}{T-t} - \frac{I-i}{t}\right)$$

* The resistance of the secondary of the transformer and the contact resistances of the brushes 4, 4′ (Fig. 4), which connect the secondary to the commutator are here neglected. The effect of these resistances is to assist commutation, so that the conditions chosen are worse than in practice.

† i flows through both portions of the secondary in series.

The condition for sparkless commutation is therefore

$$\frac{RT}{L} > 1, \quad \text{or} \quad R > \frac{L}{T}$$

or

$$2IR > \frac{2IL}{T}$$

The reactance voltage is $2IL/T$, and $2IR$ is the total voltage-drop at the brush A. Hence the reactance voltage must again be not greater than the voltage-drop at one brush contact.

The value of L depends on the inductances of the primary and secondary windings of the transformer, the mutual inductance between them, and the inductance of the armature winding between the slip-rings. It

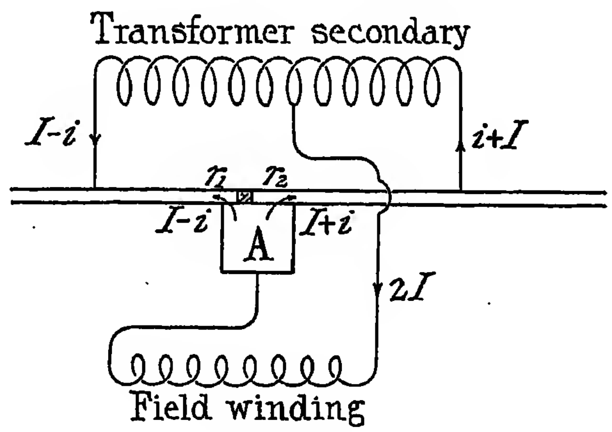


FIG. 11.

is also dependent on the resistance in the primary circuit if this is large.

Let L_1 = inductance of primary of transformer;
L_2 = inductance of secondary of transformer;
L_a = inductance of armature between slip-rings;
M = mutual inductance of primary and secondary;
R_1 = resistance of primary winding;
R_a = resistance of armature between slip-rings.

Then if an alternating current of frequency f be supplied to the secondary the equivalent inductance will be

$$L = L_2 - \frac{M^2(L_1 + L_a)4\pi^2f^2}{4\pi^2f^2(L_1 + L_a)^2 + (R_1 + R_a)^2}$$

$(R_1 + R_a)$ is small in comparison with $(L_1 + L_a)$ and may be neglected.

$$\therefore\ L = L_2 - \frac{M^2}{L_1 + L_a} = L_2 - \frac{\eta^2 L_1 L_2}{L_1 + L_a}$$

where η is the coupling coefficient.

In transformers η is very high (of the order of 0·98 to 0·99) and, since L_a is small in comparison with L_1, L is the difference between two quantities of very nearly the same value. Any inaccuracy in the determination of L_1, L_2 and η will therefore make a considerable error in the value of L.

When η is high, however, we can, without appreciable error, substitute for L in the following way:—

Let L_p = inductance due to leakage in the primary;
L_s = inductance due to leakage in the secondary;
n_1 = number of primary turns;
n_2 = number of secondary turns.

Then

$$L = L_s + (L_p + L_a)\left(\frac{n_2}{n_1}\right)^2$$

L_p and L_s can be measured by short-circuiting, say, the secondary winding and applying a low-voltage V at frequency f to the primary. A wattmeter and ammeter are placed in the primary circuit. Then if W is the reading on the wattmeter, and I the reading on the ammeter, the equivalent inductance in the primary is

$$\frac{V}{2\pi f\sqrt{[I^2 - (W/V)^2]}}$$

This is equal to $L_p + (n_1/n_2)^2L_s$. Usually, without much error, $(n_1/n_2)^2L_s$ can be taken as equal to L_p

$$\therefore\ L_p = \frac{V}{4\pi f\sqrt{[I^2 - (W/V)^2]}}$$

and $L_s = (n_2/n_1)^2L_p \quad \therefore\ L = (n_2/n_1)^2\{2L_p + L_a\}$

The average of a number of tests gave $L_p = 0{\cdot}0018$ henry. The armature inductance, L_a, was measured with a steady current of 20·7 amperes flowing in the field and was 0·0137 henry.

TEST OF THE LIMITING CURRENT FROM THE RECTIFIER WITH SPARKLESS COMMUTATION FOR A GIVEN RATIO.

The full primary of 440 turns and a secondary consisting of two adjacent secondaries of 16·5 turns were used, giving a ratio of 440/16·5 = 26·7/1. The field was separately excited from a battery with 20·7 amperes, i.e. the same as was used in the test of L_a. The speed was maintained constant at 850 r.p.m. The rectifier was loaded by means of a reactance consisting of the winding of a transformer in series with a variable carbon-block resistance. The number of turns of the transformer could be varied, but they were always sufficient to keep the rectified current steady, i.e. no indication was obtained on an induction ammeter.

The tests were taken in semi-darkness and the results are given in Table 6.

TABLE 6.

Transformer primary P.D.	Rectifier current	Field current	Speed	Remarks
volts	amps.	amps.	r.p.m.	
310	24·5	20·7	850	No sparking
310	40	20·7	850	Slight sparking under brush
310	50	20·7	850	Slight sparking under brush
310	60	20·7	850	Definite sparking
310	75	20·7	850	Bad sparking

NOTE.—Brush 5 in neutral position during test. Brush pressure = 14 lb. per sq. in.

Before tests were taken the machine was run for half an hour with 25 amperes from the rectifier, to warm the brushes and get a steady condition.

The precise current at which sparking commenced was indefinite. At 25 amperes there was definitely

no sparking. At 40 amperes there was slight sparking under the brush. At 50 amperes the sparking was still slight and under the brush. At 60 amperes the sparking was quite definite and at 75 amperes it could be described as very bad. In ordinary daylight, and without close examination of the brush, no sparking could be detected at 40 to 50 amperes.

Value of the Current at which Sparking would be expected to take place from the Tested Values of the Inductances L_p, L_s and L_a.

The time of short-circuit is

$$T = \frac{\text{width of brush} - \text{width of mica}}{\pi d} \times \frac{60}{\text{r.p.m.}} \text{ seconds}$$

where d = diameter of commutator = 3·2 inches.

$$\therefore \quad T = \frac{0 \cdot 5 - 0 \cdot 1}{10 \cdot 1} \times \frac{60}{\text{r.p.m.}} = \frac{2 \cdot 38}{\text{r.p.m.}} \text{ seconds}$$

If $2I$ is the current flowing in the field winding, the reactance voltage (V_R) is given by

$$V_R = \frac{2IL}{T}$$

$$\therefore I = \frac{V_R T}{2L} = \frac{V_R \times 2 \cdot 38}{2 \times 850 L}$$

The ratio $\frac{n_2}{n_1} = \frac{33}{440}$

$$\therefore L = (0 \cdot 0116 + 0 \cdot 0137) \left(\frac{33}{440}\right)^2$$

$$= 0 \cdot 000142 \text{ henry}$$

With a current density greater than 40 amperes per square inch the voltage-drop of a "link C4" brush is over 1·2 volts. If we take the maximum reactance voltage permissible to be 1·2, the current at which sparking should theoretically commence is

$$I = \frac{1 \cdot 2 \times 2 \cdot 38}{2 \times 850 \times 0 \cdot 000142} = 12 \text{ amperes}$$

or a total field current of 24 amperes. This leaves out of account the effect of the contact resistances of the gauze brushes and the resistance of the secondary winding, so that a slightly better result is to be expected in practice.

Conclusion.

The question of how far such a device as that described might be useful in practice, compared with others already in use, must, of course, be left to experience to decide. The object of the tests was to indicate, as far as they go, the practical workability of the arrangement. A further object is to remove much of the prejudice which exists against the use of rectifiers, even at low voltages, although there are many purposes to which they could be applied.

The difficulty of tapping the armature of a railway motor, and of insulating the tappings against the comparatively high voltage used, probably precludes the use of the device for railway work.

It is not within the scope of this paper to discuss the question of control. It may be mentioned, however, that it was found possible to run the motor in the ordinary way and to switch on the transformer and rectifier with the armature still connected to the field winding. With a suitable ratio in the transformer, and with the rectifier arranged to strengthen the field, the motor gradually became a generator. The armature could then be disconnected from the field and switched on to the line, giving the same arrangement as that used in the tests. The regenerative effect then became stronger.

From the characteristics as a generator it can be deduced that a comparatively large drop in line voltage would not involve heavy increase in regenerated current and braking effect, and some preliminary trials with changing voltage have borne this out.

A high brush pressure in the rectifier, though not so high as in these tests, is required. No evil effects resulted from the brush pressures used, and the rectifier ran for long periods without any blackening or smearing, and no attention was needed whatever under normal conditions.

In conclusion, the author would like to thank the directors of the Technical College, Dundee, for permission to carry out these tests.

DISCUSSION ON

"THE DRIVE OF POWER STATION AUXILIARIES."*

NORTH-WESTERN CENTRE, AT MANCHESTER, 20 NOVEMBER, 1923.

Mr. W. Eccles: Until now the opinions expressed by many engineers have been very confused, the real object of the various auxiliary systems being lost sight of under a cloud of words such as "heat balance," "house set," etc.; the whole question being generally confused with feed-heating. The present paper clears away a great deal of this confusion and gives us a picture of the whole problem as it occurs in a modern station containing turbo sets of from about 20 000 to 25 000 kW. The authors appear to be prepared to spend an unlimited amount of money to obtain reliability, but they do not attempt to state what the loss incurred by a shut-down is, and I should be glad if they would indicate the saving to be expected by avoiding stoppages and thus justifying the extra expenditure on reliability. It seems to me that the loss due to interruption of supply comes under two heads: (1) Loss of reputation by both the supply undertaking and the engineer. I have no doubt that these have a cash value, but I suspect that their influence on the design of the plant is felt to a greater degree than the cash value would indicate. (2) The aggregate loss sustained by the individual consumers. This is probably greater than the supply undertaking's liability and is different for each type of consumer. It depends, however, on the average to a large extent on the time of stoppage, although in some cases the maximum damage may have been incurred in the first few minutes. The liability to interruption can no doubt be greatly lessened by the adoption of a particular scheme of auxiliary drive, but the time of interruption depends more on the arrangements for controlling the power generation, distribution, conversion and application than on the scheme of auxiliary drive adopted, and I should say that this question of control generally and of auxiliaries in particular should be given more attention than it is to-day, if the extra expense for reliability is not to be thrown away by the increased duration of the stoppage. American practice would appear to be ahead of English practice in this respect. The time required to recover full load again seems to be some function of the number of attendants involved and the means adopted for each one to advise his colleagues what the position is. It would seem that in these large stations there should be more centralized control either by remote-operated valves, etc., or by detail signal from a central point to individual control points where the attendant is within reach of all the controls of the valves or switches, etc., to be operated. From accounts published in the Press it would appear that the larger the system the longer the period of stoppage whatever the cause, and for this reason the reliability of superstations as measured by the total stoppage time per annum may very well be no better than that of the smaller station. It would seem then that reliability cannot be dealt with alone and that ease of control must go with it. In regard to the question of working efficiency, the authors do not point out that there can be very large differences in efficiency between two similar systems each heating the feed water up to the same temperature, with prime movers of equal efficiency. The invisible loss which can occur is due to waste of heat-drop—not waste of heat, which is usually fairly obvious—and the easiest way to compare the efficiency of such plant is to note for each system the aggregate of such heat-drop losses. These losses mostly occur wherever steam is being transmitted from one place to another, through pipes and valves, or where heat is being transferred from steam to water, the loss at each point being proportional to the total number of heat units transferred, multiplied by the mean difference in temperature between the steam and the water. In other words, wherever hot steam is used in heating cold water there is a loss of potential work. This is one of the drawbacks of the scheme in which a house set exhausts into a feed heater, where a mean drop of 50 degrees F. may easily occur, due to the low ratio of feed water to steam condensed, or indeed at any point where the temperature of the water is increased by a large amount in one stage of heating. The authors do not appear to pay much detailed attention to capital cost; otherwise I think their views on the types of auxiliary supplies might have been more definite. I have put together some approximate comparative figures on capital cost and efficiency for the auxiliary supply for a 33 000-volt, three-phase, 25-period station, with steam at 250 lb. per sq. in. and a total temperature of 650° F., and with water at 75° F., the d.c. auxiliary motors totalling about 1 000 kW per unit of 20 000–25 000 kW. Comparing the auxiliary drive from the main busbars via transformer and motor-generator with that of a condensing house set of the same capacity, I find that with a main turbine of 80 per cent thermodynamic efficiency, an alternator of 96 per cent efficiency and a motor of 93½ per cent efficiency, neglecting switchgear and cable losses, the resultant comparative efficiency is 70 per cent at the generator coupling and the capital cost approximately £10·5 per kW. In the case of a geared condensing house set of 1 000 kW under the same conditions we get a thermodynamic efficiency of 70 per cent with gears of 98½ per cent efficiency. This gives a resultant comparative figure of 69 per cent efficiency at its corresponding generator coupling, and the capital cost approximately £5·7 per kW as against £10·5. In other words, it costs in capital nearly twice as much to obtain power for the auxiliary drive if it is taken from the main busbars, and the coal cost per unit is practically the same, or perhaps one should say that it costs £5 000 more to get 1 000 kW from the main busbars than it does to get it from a condensing house set. This particular case may be an extreme

* Paper by Messrs. L. Breach and H. Midgley (see vol. 61, p. 829).

instance, but in any case capital cost is a vital point for most station engineers to watch, and I should like the authors to say whether they consider it would ever pay to take auxiliary power or, indeed, any such small amount of power from the main supply of a super-station. Although the authors have limited their remarks to large stations, I should like to ask them if they can state at what size of smaller station or unit they would cease to advocate the use of divided auxiliary supply and double-auxiliaries. It appears to me that for 10 000-kW units the case is very doubtful. In fact, I do not think that one can make out a case for the divided supply or drive, except perhaps in the case of the circulating pump.

Mr. H. C. Lamb: Most of the good points in the paper may, I think, be fairly claimed as being already standard practice in Manchester. All who are engaged in power station work, and particularly those who have ever been in charge when a bad short-circuit has occurred on the high-tension system, followed by a shut-down of the auxiliary plant, are fully alive to the importance of this subject. The authors have given their view of the relative importance of the various parts of the plant and there is only one point to which I would take exception. The circulating water pump comes easily first, but they have included, as of equal importance to it, the air-extraction pump, which is hardly correct. I have known cases where the air-extraction pump stopped for several minutes while the plant was on load, without any very serious fall in vacuum, and I think that this auxiliary ought to come in Class B or Class C. I quite agree with the authors in deciding in favour of electric drive throughout; the steam drive, of course, has its merits, but there are some things which are decidedly against it. As has been mentioned, there is the high cost of maintenance and attendance, and, particularly with high-pressure schemes, the undesirability of adding further small pipes and valves. On page 834 the authors say, "any extra economy obtained by the use of steam-driven auxiliaries," and, in the paragraph below, "it is assumed that feed heating by steam from the main turbines is the case all through." There certainly is no economy in the use of steam-driven auxiliaries in such a case. For economy, the electric drive is easily first, and the drive through the combined house-service turbine and transformer, i.e. the double system, comes second. Certainly the all-steam drive comes last in economy. The authors rightly put reliability first, and some of these schemes are certainly not safe. In Schemes 2 and 3, for instance, the principal motors are all connected to the main a.c. system, and would very likely pull out and shut down if a bad short-circuit occurred in, or near to, the station. One would not like to place too much reliance on the scheme which the authors set out for a house-service set to be run up and put on the bars in 10 seconds merely by pressing a button. Presumably this would have to be done as soon as it was known that trouble was brewing, but the difficulty is that one never does know until too late. Schemes 1, 3 and 4 include a special generator on the main shaft. That is a particularly interesting proposal and, I think, a new one. It is, no doubt, very economical, but has one disadvantage in increasing the length of the main plant, and another in that the special generator would not be available for running the auxiliary plant during the preliminary starting-up of the station, when there is a great deal of running up and shutting down. Scheme 6 seems to be very expensive in switchgear and, like Scheme 7, has the objection that d.c. motors are used. The one advantage of the d.c. motor is, as the authors state, in speed variation, but there is not very much need for speed variation in the power station auxiliaries. So far as I know, there are only two classes of auxiliary plant which need a variable speed, and they are the stoker motors and boiler fans. With regard to the former, as these are small motors it is quite easy to get the regulation by means of a rotor resistance. In the case of the boiler fans d.c. motors are certainly a great convenience. They assist in keeping a steady steam pressure, and the draught can very easily be regulated. There is also some gain in economy by having variable-speed instead of constant-speed fans, but this economy is not very great. In a particular case, allowing a reasonable number of hours on a light load, the saving was only 0·1 per cent of the boiler output. If it is really desired to use a.c. motors this very small saving is hardly worth consideration. There is no doubt that a great many troubles are eliminated if direct current is not used. The authors sum up in favour of Scheme 7, which makes use of a house-service set. This has a great many advantages, particularly in starting up new plant. All the auxiliary plant can be run up and tried out and put into good order before the time comes for starting up the main plant. In my opinion the best scheme is the one given as the alternative to Scheme 7. There is no detailed description because, I suppose, the scheme is so simple that this is not needed. Alternating-current motors are used throughout with a house-service set and an alternative supply from a transformer off the main busbars. When dealing with this alternative arrangement the authors say: "Such a modification would probably reduce the first cost, but would entail additional complications in running, because of the necessity of synchronizing the a.c. supplies at times of emergency, and also because of the probability of any fault shutting down the motor-generators and so rendering the battery of no use at the very time when it is most needed." I wish the authors would specify exactly what the emergency is which would require the synchronizing of the two supplies, because it is an essential feature of such a scheme that the two supplies should never be synchronized. If one supply fails it is quite an easy matter to make good the essential parts of the auxiliaries from the other supply. Also, with such a scheme a battery is unnecessary. The authors say little on the subject of suitable voltages. Some large stations have used high pressures (2 000 volts or more) and have justified their action on the ground that it resulted in a saving in switchgear and cables. I had occasion to check a case of this kind where some 300-h.p. motors were used. For 2 000 volts, as compared with 400 volts, the switchgear and motors cost more, whereas the cable cost less, but, on the whole, the balance was 7 per cent in favour of 400 volts. Of

course everything depends on the length of cable which has to be used. In this case the total length of cable was 250 yards for the whole of the motors. Had 500 yards of cable been required the total cost of motors, switchgear and cables for the two cases would have been about equal, but no one would want to use 2 000 volts without some very considerable saving, because so high a voltage does introduce an additional complication, being unsuitable for motors below about 50 h.p.

Mr. A. Stubbs: The paper might be concisely expressed as follows: "An auxiliary supply must have reliability with economy, more or less regardless of the expense." The subject matter deals almost entirely with the relation between reliability and economy; indeed it would be safe to say that the paper could never have been written had not the large turbo-alternator set been accepted as being a more economical source of supply than the smaller turbo set. In the light of certain developments in the design of large turbines which have taken place within the past few months it would appear that the foundation of the paper may be cut away. Large turbines of, say, 20 000 kW and more are being offered and built as two-cylinder units, the special feature being that the high-pressure cylinder has a remarkably high efficiency so that the complete unit gives a thermodynamic efficiency of something over 80 per cent. The small back-pressure turbine may be made to operate at a high thermodynamic efficiency which would compare with the above figure. We may now consider the main double-cylinder turbine operating on the steam side in parallel with a back-pressure turbine driving the house-service generator. The low-pressure cylinder of the main set would exhaust to the condenser, whilst the back-pressure turbine would exhaust to the connection pipe between the high-pressure and low-pressure cylinders of the main set, or alternatively, in case of emergency, to atmosphere. Back-pressure turbines have previously been considered for house service, but must now be regarded in the light of the following new conditions: (*a*) Economy of the small unit. (*b*) Convenience of the double-cylinder design of the main set in so far as it provides a suitable point at which the exhaust from the back-pressure unit may pass to the low-pressure cylinder of the main unit. (*c*) The state of the steam from the back-pressure unit will be similar to that from the high-pressure unit of the main set, and ample provision can be provided for adequate mixing of the steam before passing to the low-pressure cylinder. (*d*) The high-speed turbine in conjunction with gears makes for a more efficient back-pressure unit. In addition to maximum economy the arrangement would also provide for: (*e*) Maximum reliability, since the back-pressure house set would be entirely independent of the condenser and its auxiliaries, also of the main alternator busbar and the large oil switches. (*f*) A number of back-pressure house-service sets could be conveniently paralleled and easily isolated in the event of a fault. (*g*) The back-pressure units would be almost equally suitable with either d.c. or a.c. generators, whilst the d.c. supply would be little, if any, more expensive than the a.c. supply. (*h*) The battery for the emergency supply to auxiliaries may be eliminated on account of the facility for immediate starting of the back-pressure sets. (*i*) The house set could be conveniently placed in the annexe between boiler house and power house, where space is probably not nearly so expensive as in the main power house. (*j*) It is not necessary to parallel the house service supply with the main power station busbars, and this should tend to reduce capital cost and increased reliability in so far as an additional link is removed from the chain.

Mr. S. L. Pearce: In regard to Mr. Eccles's remarks on the subject of reliability, I think that it is not a question of the engineer's reputation, nor is it one of the aggregate losses that may be suffered by the consumers on the system. The point is, that if a system gets a bad reputation for interruptions to the supply the undertaking will not get new and important business which it otherwise would do, and which it is very desirable it should receive. In reply to Mr. Stubbs, I do not think it necessarily follows that the house-service arrangement requires additional space. I know that it does not so far as the Barton station is concerned. The main dimensions of the turbine room would not have been altered if we had not adopted house-service sets. The foundations for these sets were not so expensive as Mr. Stubbs imagines. Whilst I think that the question of reliability of operation is the first requisite to be considered (followed by thermal efficiency and then capital outlay), at any rate in the case of stations that the authors have in mind, the type of drive and the source of power as affecting the station heat balance must not be lost sight of. Therefore it is most important to consider from every aspect the various methods of obtaining the auxiliary supply. There is no doubt that, from the thermal efficiency point of view, an auxiliary supply which is derived, either directly or indirectly, from the main generating plant, either through a service transformer supplied from the terminals of the main generator or from the main busbars, is the most economical. In passing, I think that we should now have to consider as a further alternative the question of the supply being obtained from an auxiliary generator coupled direct to the end of the main generator shaft. The remaining alternatives are (1) a dual supply from house-service sets and house-service transformers and (2) steam-driven auxiliaries. When we take into consideration the factor of reliability I think there can be no doubt that the former method is the better, viz. house-service sets in conjunction with house-service transformers, and I rather gather that that arrangement is the one considered by the authors to be the best—at the moment at any rate. The house-service generator as a source of power and of steam for feed heating has achieved a considerable measure of popularity, and it will in my opinion continue to warrant its adoption until such time as it can be definitely shown that the advantages to be derived from a system of multiple-stage "bleeding" of the main turbine for feed-heating purposes are so great as to preclude the adoption of other methods. A word or two with regard to the actual arrangement which has been adopted at Barton station may be of interest. The two alternative sources of auxiliary supply are, first, from three house-service

three-phase turbo-alternators, operating at 420 volts and exhausting into a condenser-heater which also receives the exhaust from the steam-driven boiler feed-pumps. The house-service sets therefore perform a most important function in connection with the heating of the feed water. As an alternative source of auxiliary power supply we have house-service transformers, stepping down the 33-kV busbar voltage to 420 V. All the motors—at any rate so far as they relate to services of primary importance—are divided equally between those two sources of supply. Auxiliary busbars are provided, one set of bars being energized and supplied from the house-service sets, and the other set from the house-service transformers. With regard to the duplicate motors for these important services—taking the circulating pumps as an example—one motor would be coupled to bars supplied by the house-service generators and the second would be coupled to the bars supplied by the house-service transformers. Normally these auxiliary power bars are kept isolated, and there are three sections of each corresponding to the three main units in the station. These sections are not normally coupled together, though provision is made for so doing in case of emergency. The total horse-power of all motors installed is 7 000, and of that total only 170 h.p. is for d.c. motors, these being in the main for the turbine house cranes. I do not see very much scope for the employment, on a large scale, of storage batteries for auxiliary purposes. At Barton we have only two batteries, the main battery being to provide a standby for excitation and for station lighting, and the second being a switch-trip battery. I agree with what has been said with regard to the method of coupling auxiliary power machines on to the end of the main turbo-generator shaft. Previous speakers have referred to certain objections to that method, e.g. the increase in the length of the set, and I should like to ask whether there are not two other difficulties. I take it that the machine would have to be of rather a special character, having regard to the speed of the main unit. Secondly, owing to the fact that the critical speed of the special generator shaft would not be that of the main generator shaft, it would necessitate the introduction of a flexible coupling and perhaps additional bearings. With regard to the use of steam-driven units, I think that the use of such sets for small auxiliaries must, in the future, decline with the advent of the higher boiler pressures now employed.

Mr. W. Dundas: The subject appears to me to have been considered principally in conjunction with the large station, and one speaker has mentioned that duplicate auxiliaries should not be adopted on units of less than 10 000 kW capacity. The smaller stations are equally important as regards reliability of supply, and should be considered. With a single set of auxiliaries the duplicate drive can be obtained by the employment of a motor and steam turbine coupled together. The steam to the turbine would be automatically controlled so as to bring the turbine into action in the event of failure of the supply to the motor. Such an arrangement enables advantage to be taken of the electric drive, which would be the normal running condition, and provide the reliability connected with the steam drive in cases of emergency. Arrangements would have to be made to prevent the motor from supplying energy to the line when the turbine was acting as prime mover.

Mr. G. A. Juhlin: The authors wish to have an expression of opinion on the suitability of d.c. generators for direct coupling to main turbo sets for the supply of power for certain auxiliaries. The answer depends, first, on the speed of the main sets and, secondly, on the output required from the d.c. generators. For 1 500-r.p.m. sets the scheme is quite satisfactory for any size of main sets that may be required. Units of 15 000 kW capacity have been in satisfactory operation for some years with d.c. generators direct coupled to main sets. The problem becomes much more difficult, however, when 3 000-r.p.m. sets are considered. The question of output required becomes of importance. Small units of, say, 150 kW at 500 volts which can be overhung on the generator shaft may be considered satisfactory. I understand that something like 500 kW would be required for the auxiliaries of a 25 000-kW set, and I do not think that one could recommend building a 500-kW d.c. generator at 3 000 r.p.m. There are, of course, d.c. generators of this output running at about 2 500 r.p.m., but one cannot say that the reliability is such as would be required for power station auxiliaries. The authors point out the absolute necessity for reliability of the particular auxiliaries supplied from the direct-coupled d.c. generators, and I should certainly hesitate to recommend the scheme. It should be remembered that the difficulties in operation of a d.c. generator direct coupled to a large mass such as a main unit are greater than when operating it as an independent unit. To sum up: For 1 500-r.p.m. sets the scheme is satisfactory, while for 3 000-r.p.m. sets it should be avoided if at all possible.

Messrs. L. Breach and **H. Midgley** (*in reply*): We think that Mr. Eccles rather underestimates the detrimental effects of a shut-down. We are fully in agreement with the remarks of Mr. Pearce on this point, and would add that the moral effect of a series of shut-downs is not conducive to efficiency of working; in other words, the effect is apt to be cumulative. We would also refer Mr. Eccles to the remarks of Mr. Brazil in the London discussion (vol. 61, page 846). That the time of interruption depends also upon the distribution arrangements, etc., is true, and, whether or not the distribution system be the greater factor, it is essential that the auxiliary system should be such as not to be affected by external disturbances, and the auxiliary arrangements must therefore be given equal attention.

We have to thank Mr. Eccles for the figures as to the capital costs of the two alternative arrangements. We would suggest that the true relative values are best realized by considering the costs as fractions of the cost of a complete power station, when it will be seen that the difference between the two arrangements is only approximately 0·5 per cent of the total cost of the station. The question of maintenance and attendance must also enter into the comparison.

Regarding the point at which divided auxiliaries would be recommended, it is suggested that this

depends upon two factors: (1) The importance of continuity of supply from the particular station and its relation to other generating stations (if any) on the system; (2) the possibility of detriment to the turbine through atmospheric running.

Mr. Lamb's point regarding the air-extraction arrangement has been dealt with in the reply to Mr. Jockel in the London discussion. The question of choice between alternating and direct current for auxiliary motors has already been dealt with so fully in the previous discussions on this paper that we do not consider it necessary to add anything further. The "synchronizing in times of emergency," mentioned in the paper in connection with the alternative to Scheme 7, refers to the possible necessity of changing over the auxiliaries and groups of auxiliaries from the main bars to the bars fed by the house turbine, without shutting these auxiliaries down. With direct current this could easily be done, but in the case of alternating current it would be practically essential to have the two supplies coupled, i.e. synchronized, in order to avoid shutting down when changing over. We are fully in agreement with Mr. Lamb's statement that a considerable saving in cost must be shown before it is worth while adopting a pressure of 3 000 volts for auxiliaries, in view of the fact that it is unsuitable for motors below about 50 h.p.

The suggestions of Mr. Stubbs are noted with interest, but, while we agree that they are worthy of consideration and comparison, they by no means cut away the basis of the paper. Incidentally, we rather suspect that the scheme would not be quite so simple of operation as Mr. Stubbs so optimistically suggests.

As already stated, we are in thorough agreement with Mr. Pearce regarding the effects of a shut-down. The information regarding the auxiliary arrangements at the Barton station is noted with interest. The question as to the effect of the size of the station upon the auxiliary arrangements, raised by Mr. Dundas, has been dealt with in the reply to Mr. Eccles. The suggestion by Mr. Dundas of having a turbine and motor driving the same auxiliary has been adopted in at least one large station in this country, and to the best of our knowledge the scheme is working satisfactorily. It has, of course, the same objections as have already been raised in the paper regarding a direct steam drive.

We thank Mr. Juhlin for the information which he gives as to the suitability of d.c. generators for direct coupling to main turbo-alternator units.

DISCUSSION ON

"THE LEAKAGE FLUX BETWEEN PARALLEL POLE-CORES OF CIRCULAR CROSS-SECTION." *

Dr. A. E. Clayton (*communicated*): I have read Mr. Hague's paper with much interest. The fact that poles of circular cross-section are now not generally favoured by designers does not in the least detract from the value of the simple expression deduced by the author for the leakage permeance per cm height of pole, or from the value of the graphs plotted in Fig. 3 of the paper. In practice, some designers utilize a value of the Hopkinson leakage coefficient based upon experimental results on previous machines. Others, as pointed out by the author, calculate the value of the leakage flux by the method due to Arnold, in which the leakage lines at the ends are assumed to have the form indicated in the second quadrant of Fig. 4, as suggested first by Forbes. Yet others employ a method in which the leakage flux at the ends is "scientifically guessed." At present, then, designers experience difficulty in calculating the leakage which occurs at the ends of the poles. For dealing with circular pole-cores, Arnold based his calculations upon the "equivalent square" pole, as indicated in Fig. 4. The assumed flux distribution at the ends is obviously incorrect, so that the leakage flux, as calculated by Arnold's method, is too low. This statement will also hold for all cases where the corresponding Arnold formulæ are used, and thus applies in particular to the case of square and rectangular poles. In this connection, emphasis may well be laid upon the author's statement that "the permeance calculated from any assumed distribution of lines of force other than the true distribution must of necessity be too small," as this important principle is often overlooked. When Arnold's method is applied to the case of circular poles, the calculated value of the leakage permeance per cm height of pole is too low. The actual error varies in amount by about 1·5 to 1·7 for the cases dealt with in Table 1. When the distance between poles is relatively great, however, the value calculated by the Arnold formula is worthless, the percentage error being enormous. This is, of course, to be expected, as under these conditions the leakage at the ends of the machine is very important. The percentage error, however, decreases rapidly as the relative value of the clearance between poles decreases. When the distance between poles is relatively small, it is natural to conclude that the

* Paper by Mr. B. Hague (see vol. 61, p. 1072).

actual configuration of the pole will have a relatively greater influence upon the actual value of the leakage flux than when the poles are very far apart. It may then, I think, safely be concluded that the actual value of the leakage flux for the case of circular poles will not differ to any serious extent from that obtaining in the case of the "equivalent square" poles. The error obtaining with the Arnold method may therefore safely be assumed to be due to the fact that this method, by assuming a wrong flux distribution at the ends of the machine, much under-calculates the corresponding leakage, and not to be due in any marked extent to the conception of replacing the circle by the equivalent square. By using the data given in the paper, therefore, we are now in a position to deal more exactly than hitherto, not only with the case of circular pole-cores, but also with poles of other section. Thus, for dealing with poles of square section, it would appear that the value of the leakage flux can be estimated more correctly than by means of Arnold's formula if the calculations are based upon the "equivalent circular pole." The value of the leakage permeance per cm height of pole can then at once be read off from the graph given in Fig. 3. Pole-cores with semi-circular ends can also be handled with sufficient accuracy without any difficulty, and a rectangular section may be replaced by the equivalent section having semicircular ends. I therefore regard the paper to be of value, not merely because it gives us a simple and at the same time more exact method of calculating the leakage flux of circular pole-cores, but also because the data given for circular poles enable us to calculate more exactly the leakage obtaining with pole-cores of other section. For reasons which are stated by the author and need not be recapitulated, the exact calculation of the leakage flux cannot be expected in practice, even for the case of circular poles. Still less can it be hoped to calculate exactly the leakage of a modern direct-current machine with interpoles. It would, however, be of interest if the author would give an estimate of the extent to which he would expect his results would have to be modified to deal with the case of short circular poles, of a height roughly equal to their diameter, joined by a yoke at one end and separated by a small air-gap from an armature at the other, the poles carrying a uniformly distributed winding; that is, for a case corresponding to the conditions actually obtaining in practice, with the exception that the poles may be assumed to be parallel and pole-shoes are absent. Naturally, I am asking for nothing more than a reasoned estimate, or "scientific guess."

Mr. B. Hague (*in reply*): The remarks of Dr. Clayton are of considerable interest and importance, since they enable the results obtained in my paper to be applied to a wider range of problems than I had originally visualized. With regard to the usual Arnold method of calculating leakage flux, I am quite in agreement with Dr. Clayton's conclusion, namely, that the error in the method is due not so much to the use of the "equivalent square" as to the fact that the flux assumed to issue from that square is totally incorrect. It is quite reasonable, in view of this principle, to treat other shapes of core by a kind of inverted Arnold method, using an "equivalent circle," since the solution of the problem for circular cores is so accurately known. I should like to state, however, that for square and rectangular cores the *exact* solution—found by the method of conjugate functions—is known and has been given by Dr. Douglas in the article cited in my paper. The final paragraph of Dr. Clayton's remarks raises a most important question which it is extremely difficult to answer. With a short pole-core attached at one end to an iron yoke while its other end faces an armature, the conditions of the problem become so profoundly altered that even a "scientific guess" is not easy. Dr. Douglas in his paper appears to have made an estimate of the influence of the yoke on the leakage, but his statement is not very detailed. While regretting that I cannot, at the moment, give Dr. Clayton the answer he desires, I would say that I have work in hand which will, I hope, provide a contribution towards a more complete knowledge of the leakage field. The results are not yet sufficiently advanced, however, to be usefully discussed. In conclusion, it is a source of pleasure to me to note that Dr. Clayton, as a practical designer, so thoroughly appreciates the difficulty and the importance of obtaining even approximate, but physically reasonable, solutions of flux-distribution problems.

SOME EXPERIMENTS ON THE SCREENING OF RADIO RECEIVING APPARATUS.

By R. H. BARFIELD, M.Sc., Student.

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SUMMARY.

The chief object of the investigation was to obtain quantitative information on the effect of screens, of which the dimensions are small compared with the wave-length of the waves they are intended to screen. Some preliminary experiments are described, in the first of which the screening effect of a totally closed iron tank was investigated by an operator inside it with a frame coil receiver; and in the second an investigation was made on the effect of screening a square frame receiving coil by totally enclosing each of its four sides in a metallic envelope. A description is then given of the method employed in subsequent experiments of measuring the effect of screens based upon the employment of two receiving coils connected in opposition. This is followed by an account of measurements made by this method on some specially constructed screens of straight wires, open and closed loops, and wire-netting, etc. These measurements demonstrate the important part played by closed circuits in screening the magnetic field of radio waves, and show that an effective screen may be constructed of wire-netting. In this connection a description is given of the screening of the interior of a hut with this material to protect direction-finding apparatus within it from "direct pick-up."

Further experiments, in which the effect of screens on the electric field of the waves is measured, are then described. Three types of screen investigated were shown to reduce substantially the electric field without affecting the magnetic field, while, later in the paper, it is shown that a fourth type will screen the magnetic field but not the electric field. A cage of the former type is then described which is now in practical use as a means of eliminating "antenna" effect from a single-coil direction-finder contained within it.

A discussion of the experiments follows, some explanation of the various effects being given, and conclusions are drawn as to the general principles of screening and as to the essential points to be attended to in the design of efficient screens for various purposes.

INTRODUCTION.

The subject of the screening of long electromagnetic waves by conductors of relatively small dimensions has had little attention paid to it by theoretical or practical investigators. As far as the author is aware, no comprehensive theory of the action of such screens has been worked out, and very little in the nature of experimental data is available. In addition, it has been remarked that, in general, somewhat vague and contradictory ideas upon the subject at present prevail.

The experiments about to be described were therefore undertaken with two main objects in view. The first and most general was to obtain further light on the effect of conductors of various shapes and configurations on the electromagnetic fields of wireless waves, such information being chiefly interesting from a general scientific point of view. The second was to determine quantitatively the actual extent to which certain screens protect the region they enclose from the influence of radio waves of commercial frequencies, thus obtaining data which should be of some assistance to wireless engineers.

The first experiments on the screening of wireless waves were probably those of Hertz,* in which he shut off the rays of his transmitter from his receiver by means of a grating of parallel wires. With this may be coupled his experiments showing the innate tendency of high-frequency currents to concentrate on the outer members of a group of conductors in preference to penetrating within, thus demonstrating for the first time what is now known as "skin effect." More recently a considerable amount of theoretical and experimental work has been done on the effect of gratings on short electromagnetic waves. Examples of this are the mathematical work of J. J. Thomson,† and Lamb,‡ and the experimental researches of Schaefer and Langwitz,§ and that of G. H. Thomson.‖

In all the above work, however, the wave-length employed in the experiments or assumed in the calculations was always less than the principal dimensions of the screens employed; the results therefore have little or no bearing on cases involving the screening of long waves such as are used in practical radio-telegraphy where screening constructions must inevitably be small compared with the wave-length.

In this field Duddell and Taylor ¶ have measured the obstructing effects of trees to short waves; and Smith-Rose and the author ** have made observations on a wireless direction-finder receiver inside an iron airship shed and in a long metal tube, with a view rather to ascertaining the distortion produced than to determining the extent of screening. In addition to this, Smith-Rose †† has recently demonstrated the great difficulty of efficiently screening a local generator of high-frequency oscillations, by experiments which showed that even the smallest cracks in the screen would allow a considerable amount of energy to escape.

Some early experiments were carried out by Lodge ‡‡

* HEINRICH HERTZ: "Electric Waves" (translated by D. E. Jones).
† J. J. THOMSON: "Recent Researches," p. 425.
‡ H. LAMB: *Proceedings of the London Mathematical Society*, 1898, vol. 29.
§ SCHAEFER and LANGWITZ: *Annalen der Physik*, 1906, vol. 21, p. 587, and 1907, vol. 23, p. 951.
‖ G. H. THOMSON: *Annalen der Physik*, 1907, vol. 22, p. 365.
¶ W. DUDDELL and J. E. TAYLOR: *Journal I.E.E.*, 1905, vol. 35, p. 321.
** R. L. SMITH-ROSE and R. H. BARFIELD: *Journal I.E.E.*, 1923, vol. 61, p. 179.
†† R. L. SMITH-ROSE: *Proceedings of the Physical Society*, 1922, vol. 34, pt. 4, p. 127.
‡‡ OLIVER LODGE: "The Work of Hertz and His Successors."

on the penetration of waves through the walls of a cage to a receiver within, and quite lately Watson Watt and Herd * described some tests made with a frame coil and multi-stage amplifier in a specially constructed box. Campbell Swinton † has studied the directional properties of a small cylinder containing a loop receiver.

On the practical side, M. Dieckman used a screen of wires suspended horizontally above an aerial of **L** or **T** type to eliminate a certain type of atmospheric, and it is interesting to note that a paper ‡ describing this arrangement and read in 1917 gave rise to a vigorous discussion, in which those who took part apparently held distinctly contradictory ideas on the general subject of screening.

Again, many experimenters have found it necessary to employ elaborate screening arrangements for radio apparatus, and some have described their method of solving the problem, e.g. Hoyt Taylor § who employed specially screened huts for his apparatus used in connection with ground antenna. Finally, an account of work done on the subject is not complete without reference to the development of the "earth screen" as now used in modern transmitting stations. The experiments of Eckersley ‖ may be referred to in this connection.

Preliminary Experiments.

Receiver enclosed in tank.—The great difficulty of screening completely a generator of high-frequency oscillations has, as already indicated, been demonstrated by Smith-Rose. As a complementary experiment it was thought of sufficient interest to try the converse process of completely enclosing a wireless receiver in a metal case.

To make the experiment satisfactory it seemed necessary that the observer operating the receiver should be enclosed with the set. Accordingly a screen suitable for this purpose was sought for and eventually found in the form of a disused oil tank. This tank (see Fig. 1) was about 9 ft. long and 4 ft. in diameter, the thickness of the metal being about $\frac{1}{8}$ in. The only opening to the tank was in the form of a manhole 14 in. diameter fitted with an oil-tight cover and held in place by 36 nuts and bolts. The interior of the tank was divided into two compartments by means of a central partition $\frac{1}{8}$ in. thick and provided with a circular opening also 14 in. in diameter.

The receiver consisted of a square frame coil of 2 ft. 6 in. side and 30 turns, made collapsible so as to enable it to go inside the tank, and connected to a tuning condenser and a seven-valve amplifier of a standard pattern.

After preliminary tests with the apparatus in the open, this receiving set was introduced into the tank through the manhole, the operator, not without difficulty, following it. An investigation was then made of the ability to receive the spark transmission from Paris (wave-length 2·5 km) inside the tank, and the radiation from a small buzzer wave-meter situated a few feet from the tank.

The cover of the manhole was first left off. The spark transmissions from Paris could be picked up at good strength by the coil if some part of it was within a few inches of the opening, while the buzzer wave-meter could be heard loudly for all positions of the coil inside.* The cover was now put in its place, the cover bolts being inserted and screwed up one by one. Paris signals now became fainter and fainter but did not disappear until every bolt had been put in place and screwed up, while even then the buzzer could still be faintly heard.

The operator with the complete set then retired into the inner compartment through the small hole in the partition which was left unclosed. In this space no signal, local or otherwise, could be detected whether the outer manhole was open or closed. This experiment shows that the most effective way of obtaining a high degree of screening is to employ a screen within a screen.

Receiving loop with screened sides.—Two exactly similar frame coils were constructed each 2 ft. 6 in.

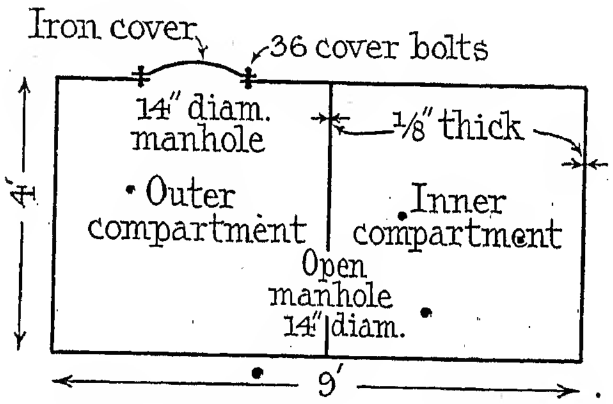

Fig. 1.—Iron tank employed in Experiment No. 1.

square by 3 in. deep and wound with 25 turns of No. 22 wire (d.s.c.). The four sides of one of these coils were completely encased in a metallic tube of rectangular section (5 in. × 3 in.) made of tinned iron (see Fig. 2), and all joints were well soldered so that the coil was completely encased except for two small holes through which the ends of the coil were brought out. The frame was carefully disposed inside the tube so that the wire was well clear of the sides of the screen. A receiving circuit with amplifier was arranged (see Fig. 2) so that it could be switched alternately from the screened to the unscreened coil, and vice versa. The tuning condensers and batteries were placed in a metal box.

Tests of this description over a wide range of wave-lengths from 1·0 to 5·0 km immediately demonstrated that the coil within the tube was perfectly screened so far as could be determined by means of this rather rough method of measurement.

The tubing was then sawn completely through at the centre of one of the sides and the test repeated. It

* R. A. Watson Watt and J. Herd: "Notes on Electromagnetic Screening," *Wireless World*, 1922–23, vol. 11, p. 532.

† A. Campbell Swinton: *Philosophical Magazine*, 1921, vol. 42.

‡ C. J. de Groot: *Proceedings of the Institute of Radio Engineers*, 1917, vol. 5, p. 75.

§ A. Hoyt Taylor: "The Use of Ground Wires at Remote Control Stations," *Proceedings of the Institute of Radio Engineers*, 1920, vol. 8, p. 171.

‖ T. L. Eckersley: *Journal I.E.E.*, 1922, vol. 60, p. 581.

* It may be as well to note that the signals received in the tank from the buzzer were quite definitely due to high-frequency oscillations and not merely to induction at the audio frequency of the buzzer, since it was necessary to tune the receiver to the buzzer wave.

was found that the screened coil now possessed a receptive power of roughly half that of the unscreened coil, i.e. the latter had to be turned to within 30° of its minimum position to get equal signal strength by the method of comparison. Varying the width of the gap in the tube from $\frac{1}{8}$ in. to the smallest possible value had no effect on the result.

The receptive power of the loop was reduced to an inappreciable value as soon as the two sides of the gap were made to touch one another, but if the gap was bridged by only a few inches of wire a distinct, though still small, pick-up was at once observable, which increased as the length of the connecting wire was increased.

The open-circuited single-turn loop formed by the metallic tubing was then tuned to the waves under

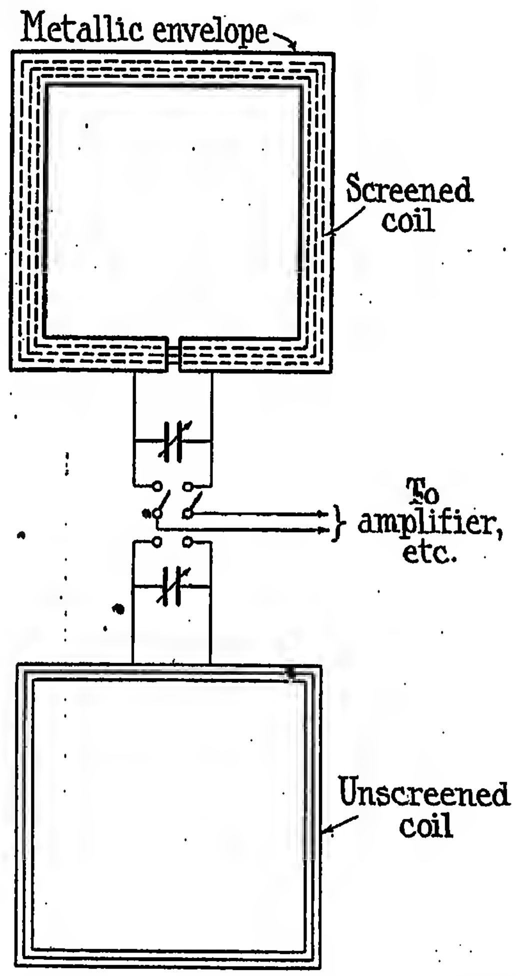

FIG. 2.—Screened loop and method of measuring effect of screen.

observation, by means of a condenser and a series inductance. The strength of signals received on the screened loop remained unaltered.

The amplifying detector was then disconnected from the inner coil (which, however, still remained tuned) and was connected to the tuned circuit, of which the outer screen now formed part. The signal strength still remained about the same, but when the inner coil was detuned, short-circuited or open-circuited, a large decrease in signal strength was noted, thus showing it was the coil and not the casing that was picking up the energy.

Since the thickness of the envelope was in each case sufficient to prevent all but a negligible amount of direct penetration of energy, that which was picked up by the coil within the casing must all have passed through the gap, thus illustrating once more how comparatively large amounts of energy in the form of oscillatory fields may readily pass through the smallest cracks in an otherwise opaque screen.

In each of the above cases it was ascertained that the screened coil possessed normal directional properties, and it was also found that with the screen connected to the amplifier box as in Fig. 3, the zeros were very sharp, showing that the "antenna" effect

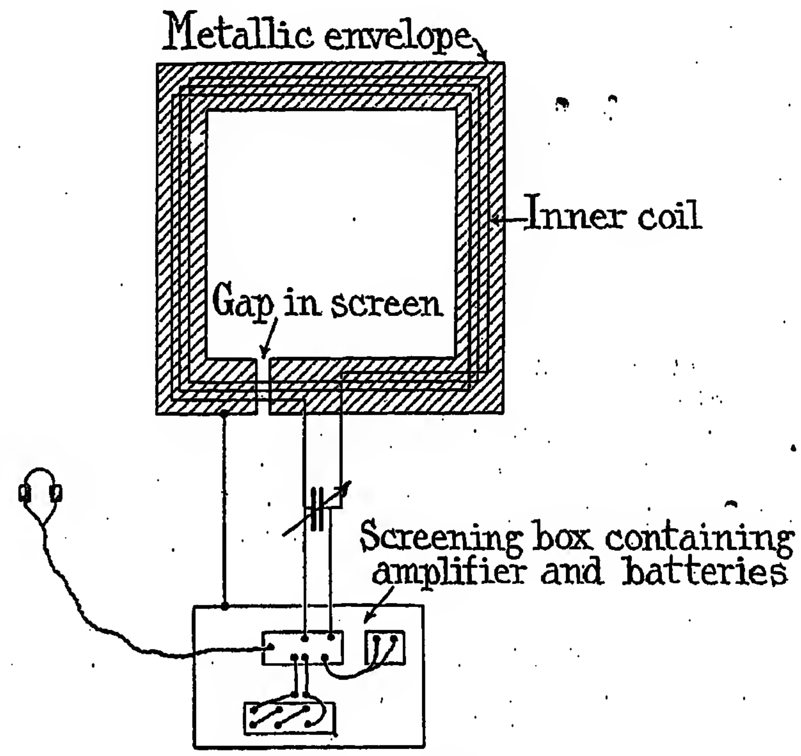

FIG. 3.—Reduction of "antenna" effect in directional receiver by screening sides.

had been practically eliminated by the action of the screen. The theoretical aspect of these experiments is discussed later in the paper.

MEASUREMENT OF THE EFFICIENCY OF SCREENING APPARATUS.

Improved method.—The rough method of measuring screening effects described above was found not to be sufficiently accurate for the more thorough experiments which had been planned. It was therefore decided to devise some more suitable apparatus.

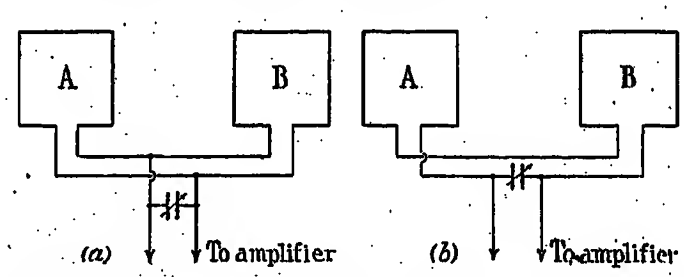

FIG. 4.—Method of obtaining a balance with spaced coils.

The basis of the method successfully adopted was to connect two receiving loops, A and B, in a common circuit so as to oppose one another when acted on by a given radio wave. This may be done in either of the ways shown in Fig. 4, i.e. the two coils may be connected either in series or in parallel across a common tuning condenser. They must in both cases, however,

be placed so far apart that the coupling between them is negligible.

The procedure was to fix one (A) in some definite position, then to rotate the other (B), which was generally the larger of the two, about a vertical axis until minimum or zero signals were obtained, noting the angular position for this condition. The coil A was then placed in the screen under investigation without altering its orientation or making any other change in the conditions. A balance was then obtained again by rotating coil B to some other position.

It is clear that the ratio in which the E.M.F. in coil B is reduced by rotation towards its minimum position will be equal to the ratio in which the E.M.F. in coil A is reduced by the screen, that is, to the ratio in which the magnetic field has been reduced by the screen. That is to say

$$\frac{H_2}{H_1} = \frac{\cos\beta_2}{\cos\beta_1} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where H_1 and H_2 are the field strengths before and after screening, respectively, and β_1 and β_2 are the corresponding angles made by coil B with the direction of the transmitting station.

It will be found on examination that the above relation holds good provided that the following assumptions are valid:

(1) That the direction and phase of the magnetic field inside the screen are the same as outside.
(2) That the screen does not appreciably affect the constants of the circuits.
(3) That the effect of any other E.M.F.'s in the circuit is of a secondary nature and may be neglected.

All these points were verified by simple experiments.

In practice it was found necessary to use compensating condensers in the manner adopted in ordinary direction-finding work for the purpose of reducing "antenna" effect. It was also found advisable to provide a switch by means of which the loop A could be reversed, thus enabling a double set of readings to be taken on each occasion, the mean of the two sets being taken for use in the calculation.

Test of accuracy of method.—A practical check on the method was obtained as follows:—

The two receiving loops, A and B, of Fig. 4, which differed considerably in the value of their "area turns," were mounted on vertical axes and separated by a distance of about 15 ft. The system was then adjusted to receive some convenient transmitter. The loop A was rotated from its maximum to its minimum position of reception in stages of 15° at a time. At each stage the E.M.F. in coil B was adjusted by rotation until a balance was attained. The angles α and β made by each coil with its maximum position were recorded for each balance position. It is clear that the ratio of the E.M.F.'s included in the two coils should be the same for each balance position, i.e. it should be found that

$$\frac{\cos\beta}{\cos\alpha} = \text{constant} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and the degree of accuracy with which this relation is found to hold will give an indication of the accuracy of the method.

The results of the experiment are recorded in Table 1, in which the value of $\cos\beta/\cos\alpha$ is found to remain very nearly constant (i.e. within 1 per cent) until the loops are within 10° of their minimum position, when divergences begin to occur. This experiment may be taken as satisfactory proof that the method is at least free from serious instrumental errors, and as evidence of the correctness of the third assumption as stated above.

Other tests for instrumental errors were carried out from time to time during the experiments, such as interchanging the two coils, comparing the results obtained from the series and parallel arrangements or altering the disposition of the leads and other parts of the circuit, etc., and in all cases it was found that no detectable variation was caused by such tests.

TABLE 1.

Test of Accuracy of Method.

Transmitting Station GLO (Ongar), $\lambda = 4\cdot5$ km.
Both Coils Unscreened.

α	β	$\frac{\cos\beta}{\cos\alpha} = K$	Difference from mean value of K (0·777)
deg.	deg.		
0	39·0	0·777	0·000
15	41·0	0·782	0·005
30	47·5	0·782	0·005
45	67·0	0·773	0·004
60	77·0	0·782	0·005
75	78·5	0·768	0·009
80	81·7	0·820	0·043
85	85·7	0·850	0·073
89	88·9	1·070	0·293
90	90·0	—	—

Again, one of the experiments (that of measuring the effect of a wire-netting cage) was repeated by another but rougher method, i.e. that already described of comparing the signal strength from two similar coils. The result agreed within the limits of the errors of the latter method, which were rather large.

FIRST EXPERIMENT: MEASUREMENT OF EFFECT OF SCREEN COMPOSED OF STRAIGHT WIRES AND OPEN AND CLOSED LOOPS.

A skeleton cube of side 6 ft. was constructed of light timber to serve as a frame for the different screens to be experimented upon. In the first place, four of its sides were covered with parallel wires (No. 20 S.W.G. copper) spaced 1 inch apart and with their ends left free, thus forming a sort of tube open at the top and bottom (see Fig. 5).

The "balanced-coil" measuring apparatus was set up as described, coil A consisting of 25 turns wound

on a 2 ft. 6 in. square frame, and coil B of 34 turns wound on a 4 ft. square frame, and the system was tuned to a transmitter working on a 4·5-km wave. A balance was obtained with coil A outside the screen, and the angular position (β_1) of coil B was noted. The screen was then dropped over coil A so that its

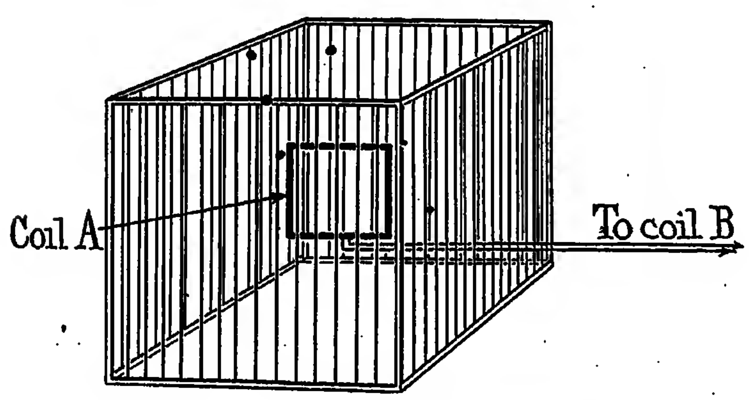

FIG. 5.—Screen of short, straight wires.

wires were vertical and so that the loop occupied the centre of the interior. A balance was once more obtained, the corresponding position (β_2) of coil B being recorded. The loop A was fixed approximately in its maximum position, but since it was not moved during the test it was not necessary to know its position exactly.

be in this case close up to it. The wires were spaced about 1½ in. apart and arranged in nine rows 2 in. apart and 6 ft. long. There were thus, in all, over 400 wires, so that the coil was situated in the centre of a mass of closely packed wires. A sketch of the arrangement is shown in Fig. 6. The method employed

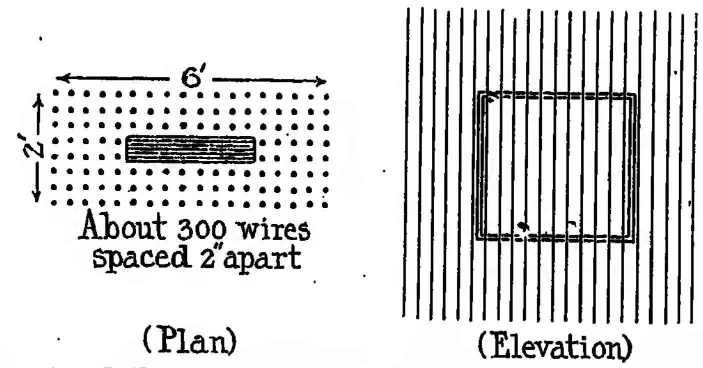

FIG. 6.—Coil surrounded by number of straight wires close together.

was quite well able to measure a change of 1 per cent in the field strength, but, as before, the screen appeared to have no effect whatever on the E.M.F. induced in the loop A, no matter whether the wires composing it were placed horizontally or vertically.

Using the same frame, a cage was now constructed of a series of conductors in the form of a three-sided

TABLE 2.

Negative Effect of Screen made of Short, Straight, Vertical Wires.

Station observed	Wave-length	Arrangement	Coil A unscreened		Coil A screened		$H_2/H_1\left(=\frac{\cos\beta_2}{\cos\beta_1}\right)$
			Scale reading at mins.	β_1	Scale reading at mins.	β_2	
	km			deg.		deg.	
Ongar (GLO) ..	4·5	Wires insulated	333·7 47·0	36·7	334·0 46·5	36·3	1·00
Aldershot ..	1·8	Wires insulated	288·5 23·0	47·3	288·5 22·0	46·7	1·01
Ongar (GLO) ..	4·5	Lower ends of wires earthed	333·7 47·0	36·7	334·0 46·7	36·3	1·00
Ongar (GLO) ..	3·9	Lower ends of wires earthed	333·5 47·7	37·1	334·0 47·5	36·7	1·00
Aldershot ..	1·8	Lower ends of wires earthed	288·5 23·0	47·3	289·0 22·0	46·5	1·01

The experiments were repeated on a wave-length of 1·8 km and again with the cage modified by connecting all the wires together at their lower ends and earthing the junction point. The measurements are recorded in Table 2, which shows at a glance that no screening effect at all can be detected for this cage, the field inside it being shown to be the same as that outside, within the limits of accuracy of the method.

The coil A was now fixed rigidly at the centre of the wooden cube from which the wires had been stripped, and numbers of straight wires parallel to the plane of the coil were stretched between two opposite faces of the cube so as completely to surround the coil and

rectangular loop [see Fig. 7 (*a*)]. These conductors were, as before, spaced about 1½ in. apart and, being 44 in number, thus covered the whole of three sides of the cube; this cage was found to have no detectable screening effect (i.e. certainly less than 1 per cent). A fourth side was now added to each loop in the manner shown in Fig. 7 (*b*), a gap being left at one corner so as to make the loops discontinuous. This arrangement was also found to have no appreciable screening effect.

The gap in each loop was now closed [see Fig. 7 (*c*)] so that the cage now consisted of a series of 44 parallel, closed loops spaced 1½ in. apart. A marked screening effect was now noticeable which was a maximum when

the plane of the loops was aligned on the transmitting station, and zero when at right angles to this direction or when the loops were placed horizontally. In the position of maximum screening, the field within the cage was found to be reduced to about 1/10th its normal value. The cage was then once more modified by the addition of a second set of parallel, closed loops at right angles to the first set and equal in number and spacing to the latter.

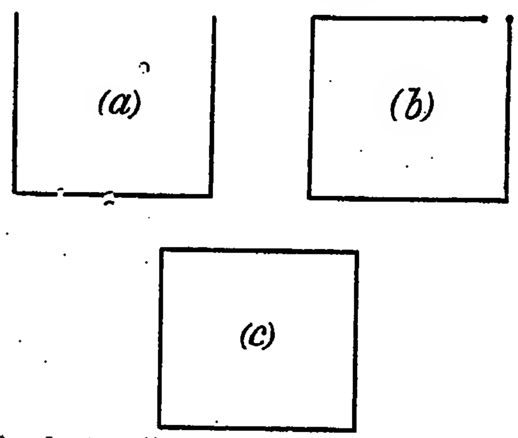

FIG. 7.—Conductor "elements" of some screens experimented with.

Tests showed that the screening effect of this arrangement was approximately constant for all orientations of the cage with the loops vertical, and equal in amount to the maximum value obtainable in the former case (i.e. with one set of loops). If the cage was turned so that one set of loops were in horizontal planes, the cage behaved exactly as in the former case when it had only one set of loops.

Further experiments were now carried out to investigate the effect of varying the number of loops forming the cage. That is to say, the overall dimensions of the cage were kept constant whilst the spacing of the loops was gradually increased by thinning them out. Measurements were made at successive stages of the process and are recorded in Fig. 8, which shows "screening ratio" plotted against spacing. It will be seen that the screening ratio falls off rapidly at first but more slowly as the spacing becomes comparable with the dimensions of the cage. With only one loop on the cage the resultant field at its centre was found to be 81 per cent of its normal value.

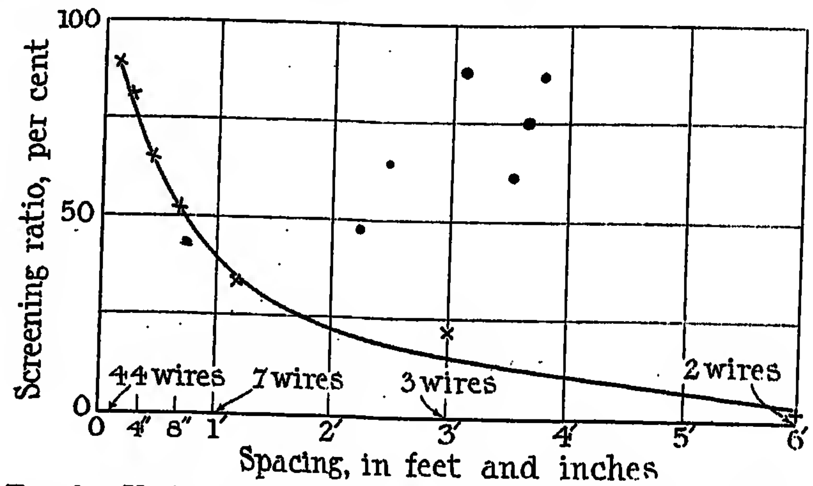

FIG. 8.—Variation of screening ratio with spacing of closed loops.

Since the value obtained for the screening ratio would be practically meaningless if the field within the cage varied greatly from point to point, a test was carried out in which the interior of the cage was explored by moving the coil A about inside it. This test showed that as long as coil A was not brought close to the boundaries of the cage the screening ratio obtained was independent of the point in the cage at

TABLE 3.

Effect of Open and Closed Loops.

Observations made on Ongar (GLO): $\lambda = 4 \cdot 5$ km.

Arrangement	β_1	β_2	$H_2/H_1\left(=\frac{\cos\beta_2}{\cos\beta_1}\right)$	Screening ratio, $1-(H_2/H_1)$
	deg.	deg.		per cent
(1) Cage of 3-sided loops [Fig. 7 (*a*)]	$\beta_1 = \beta_2$		1·00	0
(2) Cage of 4-sided open loops [Fig. 7 (*b*)]	$\beta_1 = \beta_2$		1·00	0
(3) Cage of 4-sided closed loops [Fig. 7 (*c*)] aligned on transmitter	39	85	0·11	89
(4) Cage as in (3) but loops at right angles to transmitter	39	40	0·99	1
(5) Two sets of closed loops at right angles. One set aligned on transmitter	39	85·1	0·11	89
(6) Cage as in (5) but rotated through 45°	39	83·2	0·15	85
(7) Cage as in (5) but rotated through 90°	39	83·9	0·14	86
(8) Cage as in (5) but one set of loops horizontal, the other aligned on transmitter	39	84·6	0·12	88
(9) Cage as in (8) but turned through 90° on vertical axis	39	38·7	1·00	0

The results of the experiments are given in Table 3. The ratio $1-(H_2/H_1)$ recorded in the last column as a percentage has been termed the "screening ratio" of the cage, as it was thought to be the value which most clearly expressed its screening properties.

which it was measured, thus showing that in all the central region the resultant field strength was substantially uniform. The screening was found to increase when loop A was brought close to the central wires of the cage, but became distinctly less at points near the open ends. (The experiment was carried out with only one set of loops on the frame.)

The experiments described above show very clearly that in order to screen a loop receiver it is necessary to employ closed conducting loops. In other words, they show that the presence of a system of conductors does not influence the magnetic field in its neighbourhood unless it contains closed conducting paths enclosing an appreciable area. The conducting system will even then affect only that part of the magnetic field which is normal to the plane of these paths.

sections of corrugated iron about $\frac{1}{16}$ in. thick, the sections being bolted tightly together so that the electric resistance at the joints should not be high. A comparative measurement of the field strength at the centre of each cylinder was made with the cylinder in at least two different positions. A test was also made to discover at what distance away from one of the cylinders its screening effect became inappreciable.

As before, it was assumed that the presence of the cylinders did not materially affect the constants of any part of the measuring apparatus. This was verified by the fact that no readjustment of tuning apparatus was required when the coil was set up in the cylinder. The results show (see Table 4) that a greater screening effect is obtained when the axis of the cylinder lies perpendicular to the direction of the waves than when

TABLE 4.

Screening Effect of Iron Cylinders.

Coil A, 2 ft. 6 in. square.
$\lambda = 2\cdot 9$ km.
Coils A and B in parallel.

Position at which measurement was made	Plan showing direction of axis of cylinder	Dimensions of cylinder	$\frac{\text{Cos}\,\beta_2}{\text{Cos}\,\beta_1}$	Screening ratio
	Arrow shows direction of wave			per cent
(1) Inside cylinder at centre.. ..	Coil A	Short (5 ft. dia. × 2 ft. 5 in. long)	0·72	28
(2) Inside cylinder at centre.. ..		Short (5 ft. dia. × 2 ft. 5 in. long)	0·10	90
(3) Inside cylinder at centre.. ..		Medium (5 ft. dia. × 5 ft. long)	0·38	62
(4) Inside cylinder at centre.. ..		Medium (5 ft. dia. × 5 ft. long)	0·04	96
(5) Inside cylinder at centre.. ..		Medium (5 ft. dia. × 5 ft. long)	0·37	63
(6) Inside cylinder at centre.. ..		Long (5 ft. dia. × 8 ft. long)	0·24	76
(7) Inside cylinder at centre.. ..		Long (5 ft. dia. × 8 ft. long)	0·025	97·5
(8) Outside cylinder 1 ft. away on axis		Short (5 ft. dia. × 2 ft. 6 in. long)	0·51	49
(9) Outside cylinder 3 ft. away on axis	(8) (9)	Short (5 ft. dia. × 2 ft. 6 in. long)	0·92	8
(10) Outside cylinder 6 ft. away on axis	(10)	Short (5 ft. dia. × 2 ft. 6 in. long)	0·99	1
(11) Outside cylinder 10 ft. away on axis	(11)	Short (5 ft. dia. × 2 ft. 6 in. long)	1·00	0

A study of the curve for the screen of closed loops (Fig. 8) shows that by employing closer spacing it would be possible to obtain a screen of very high efficiency. As such a screen has marked directional properties, allowing undiminished reception from the direction perpendicular to the loops, it could be used at a radio station to protect the receiver from interference from the transmitter. This method of preventing interference could be used either as an alternative to those already existing, or in addition to them, so as to obtain a greater efficiency.

SECOND EXPERIMENT: SCREENING EFFECT OF METAL CYLINDERS WITH OPEN ENDS.

Three cylinders of diameter 5 ft. and lengths 2 ft. 6 in., 5 ft. and 8 ft. respectively, were employed in these experiments. Each cylinder was built up of curved

it lies parallel to this direction, but the difference is less for the long cylinder than for the short. Although the shortest cylinder has a maximum screening ratio as high as 90 per cent, those of the two longer ones are still higher. The difference between the long and medium cylinder is not very marked, but it is enough to show that the longer the cylinder the greater is the screening ratio.

The results in (3) and (5) in Table 4 show that the medium cylinder, when upright, screens to the same extent as when it is horizontal with its axis parallel to the direction of the wave. It seems probable that this would hold good for all sizes of cylinders. At a point outside the small cylinder only 1 ft. away on its axis the screening ratio falls to 49 per cent; at 3 ft. the effect is small but easily detectable, while at 6 ft. it is only just measurable and at 10 ft. cannot

be detected. It is assumed that the maximum effect of the cylinder occurs on its axis and therefore no other positions were tried.

Third Experiment: Effect of Wire-netting Screens.

The 6-ft. skeleton cube was now covered with galvanized-iron netting of 2-inch mesh. The seams between the various lengths were bound together with copper wire so that no gaps existed of dimensions comparable with the size of the mesh, and all joints made good electrical contact. The cage so formed was insulated from the gound by standing it on small, dry, wooden boxes, and the receiving coil A of the balancing system was introduced into the interior through a temporary gap.

In addition to investigating the state of affairs at the centre of the cage with regard to both strength and direction of field, measurements were made at various other points in the cage in order to obtain a rough idea of how the field was distributed throughout the screened region. In addition, the screening ratio as measured at the centre of the cage was compared for different wave-lengths between $6 \cdot 0$ and $1 \cdot 5$ km. A small gap in the nature of a vertical slit about 3 ft. high was afterwards made in one side of the cage, but its effect on the intensity of the field at the centre was not appreciable.

The results in Table 5 show that the cage reduces the magnetic field strength of waves of $4 \cdot 5$ km to 11 per cent of its normal unscreened value. This value was not appreciably altered by a movement of the coil to other positions of the cage even quite near the sides. This seems to indicate that the field is practically uniform throughout the cage except possibly at points within a few inches of the sides, as a considerable variation at such points would not be detected by this method.

The increase in the value of β_2 obtained in (7) and (8) of Table 5 shows that coil A was approximately in its maximum position when aligned on the transmitter and inside the cage, i.e. the field was not distorted by the cage. The result in (9) tends to show that the screening effect is independent of the direction of the arrival of the waves with regard to the screen, as would naturally be expected if the cage were symmetrical about a vertical axis. The result in (11) shows that outside the cage its effect becomes inappreciable at a distance of only 5 ft. away, i.e. a length of the same order of magnitude as the linear dimensions of the cage—a result in agreement with that obtained in the experiment with the cylinders (see page 255).

The variation of screening ratio with wave-length is shown in Fig. 9, which indicates a small though definite

Table 5.

Investigation of Cages of Wire Netting.

Observations made on Ongar (GLO): $\lambda = 4 \cdot 5$ km; $\beta_1 = 39^\circ \cdot 8$; $\alpha_1 = 0$.

Arrangement	Plan	Elevation	α_2	Mean β_2	$H_2/H_1 \left(= \frac{\cos \beta_2 \cos \alpha_1}{\cos \beta_1 \cos \alpha_2}\right)$	Screening ratio
	Arrow shows direction of wave		deg.	deg.		per cent
(1) "A" in centre of cage			0	$85 \cdot 3$	$0 \cdot 11$	89
(2) "A" in centre of cage			0	$85 \cdot 1$	$0 \cdot 11$*	89
(3) "A" in centre of cage			0	$85 \cdot 3$	$0 \cdot 11$*	
(4) "A" 1 ft. from one side			0	$84 \cdot 7$	$0 \cdot 12$	88
(5) "A" in one corner			0	$85 \cdot 0$	$0 \cdot 11$	89
(6) "A" raised 1 ft. above its position in (1)			0	$84 \cdot 8$	$0 \cdot 12$	88
(7) "A" (in centre) rotated so that $\alpha_2 = +30^\circ$			+ 30	$85 \cdot 6$	$0 \cdot 11$	89
(8) As (7), but $\alpha_2 = -30^\circ$			− 30	$86 \cdot 1$	$0 \cdot 10$	90
(9) Cage rotated through 90° on vertical axis			0	$85 \cdot 0$	$0 \cdot 11$	89
(10) "A" at centre with gap in the side facing transmitter			0	$85 \cdot 3$	$0 \cdot 11$	89
(11) "A" outside cage, 5 ft. from one side ..	5—A		0	$41 \cdot 3$	$0 \cdot 98$	2

* Check readings.

Note.—α is the angle made by coil A with the direction of the wave.

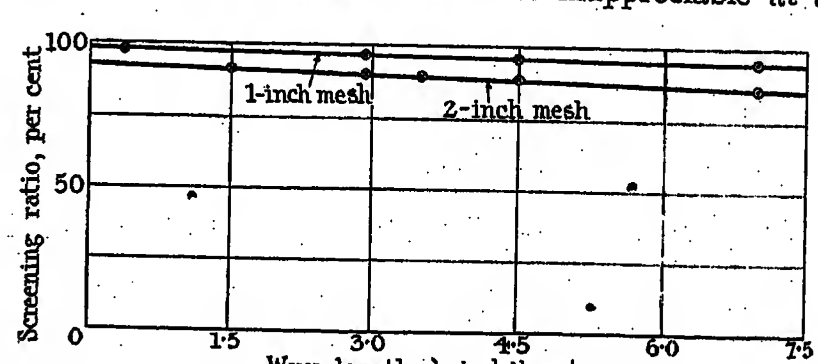

Fig. 9.—Variation in screening ratio with wave-length in wire-netting cages.

increase of screening efficiency with decrease in wave-length, the variation being linear. This seems to show that a very simple law connects screening ratio and wave-length, at least over this particular range.

One-inch mesh cage.—The 2-inch mesh netting on the cage was now removed and a 1-inch mesh put in its place. It was found that it now possessed a screening ratio of 96 per cent for a wave-length of 4·5 km, instead of 89 per cent as in the former case.

As the balance positions in this experiment occurred very near to the minimum position of the coil B in the region where, as had been shown, instrumental errors were likely to occur, several check observations were made both with A and B interchanged and with coils of different size in place of the original ones. The agreement was, however, very good, variations being in all cases much less than 1 per cent of the value obtained for the screening ratio.

The variation in screening ratio with wave-length was of the same nature as that found for the 1-inch mesh netting, and this also is plotted in Fig. 9.

Use of Wire-netting Cage as Screen for Direction-finding Apparatus.

It was demonstrated by the preceding experiment that a wire-netting cage was capable of producing more than a 95 per cent reduction of field strength and was therefore thought efficient enough to be employed for the practical purpose of screening direction-finding apparatus from the source of error known as "direct pick-up." To effect this satisfactorily it is desirable that the operator also shall be in the screen. A wire-netting cage was therefore erected inside the Bellini-Tosi direction-finding hut at Slough, being fixed as a lining to its walls, floor and roof. All seams and joints made good electric contact, as in the case of the cage in the above experiment, special spring contacts being fixed to the door, which was also lined with netting. This screen proved very efficient, for after its installation it was found that the screened apparatus did not by itself pick up any detectable amount of energy, whereas before the erection of the cage it was possible, with the apparatus entirely disconnected from the aerial loops, to obtain signals of considerable strength from ship stations and other low-power stations over 100 miles away. This type of screen possesses the advantage of being cheap and easy to construct, besides being suitable for enclosing a hut or room without interfering with its ventilation or lighting. The screen itself did not affect the accuracy of the directional measurements, since it was placed nearly symmetrically with regard to the two aerial loops and since its dimensions were small compared with those of the loops.

A Method of Measuring the Effect of a Screen on the Electric Field of a Wave.

The experiment with the screen of straight wires (page 252) demonstrated the fact which it must be admitted had not been clearly recognized before, that the strength of the magnetic field within a screen gives no necessary indication of the strength of the electric field at the same point; for in these experiments it was shown that the magnetic field was unaltered by the screen, whereas it is obvious that the electric field must have been considerably modified.

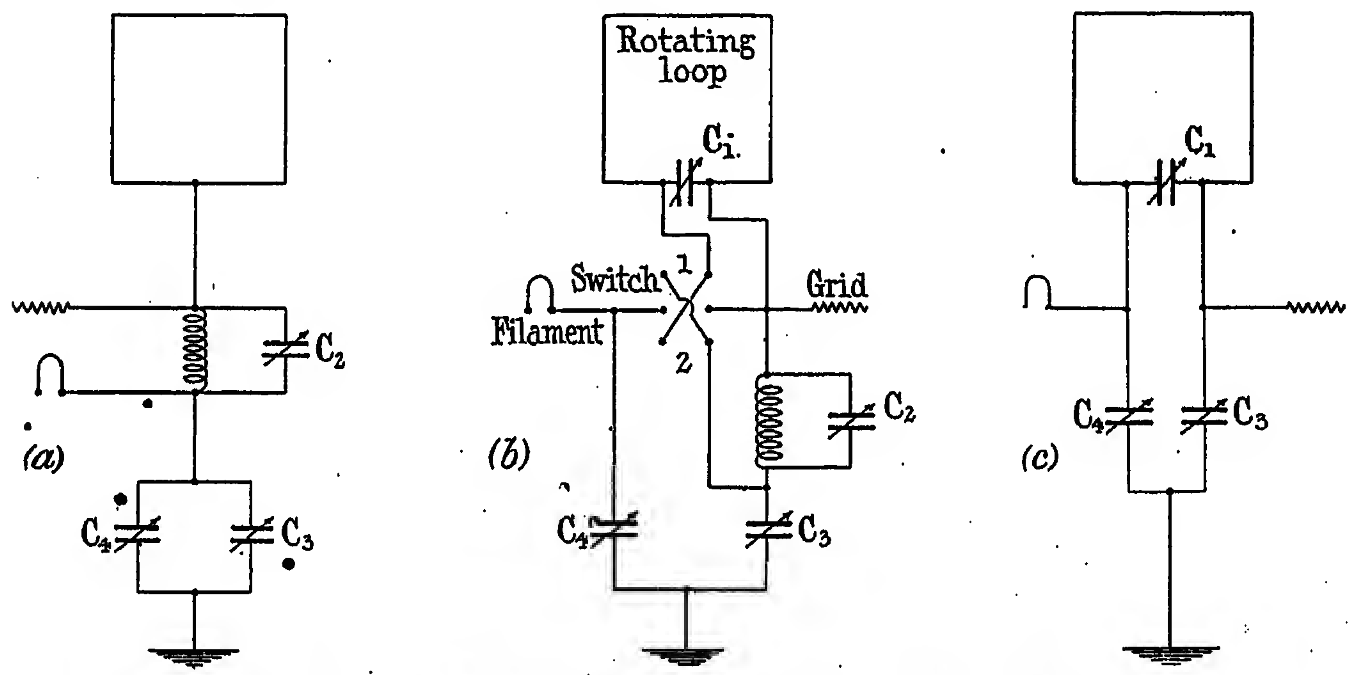

Fig. 10.—Measurement of effect of screen on electric field.

For this reason it became desirable to find a method of measuring the effect of a screen on the electric field of a wave as well as on the magnetic field. As a simple means of effecting this the circuit shown in Fig. 10 was set up. The complete circuit is shown by (*b*), while (*a*) and (*c*) show, in simplified form, the arrangements which come into operation in the alternate positions of the change-over switch.

With the switch in position (2) the apparatus is a simple single-coil direction-finder provided with compensating condensers (C_3, C_4) for the elimination of antenna effect [Fig. 10 (*c*)]. The signal strength will depend upon the P.D. (V_c) across the condenser C_1, which will be proportional to the circulating E.M.F. (E_c), for which we have

$$E_c = K_c H \cos a$$

where H is the resultant magnetic field, K_c a constant depending on the coil, and α the angle made by the coil with the direction of the wave. It is thus clear that V_c is proportional to $H \cos \alpha$.

With the switch in position (1) the apparatus is virtually an open antenna connected to earth through an auto-coupled, tuned, closed circuit and two condensers in

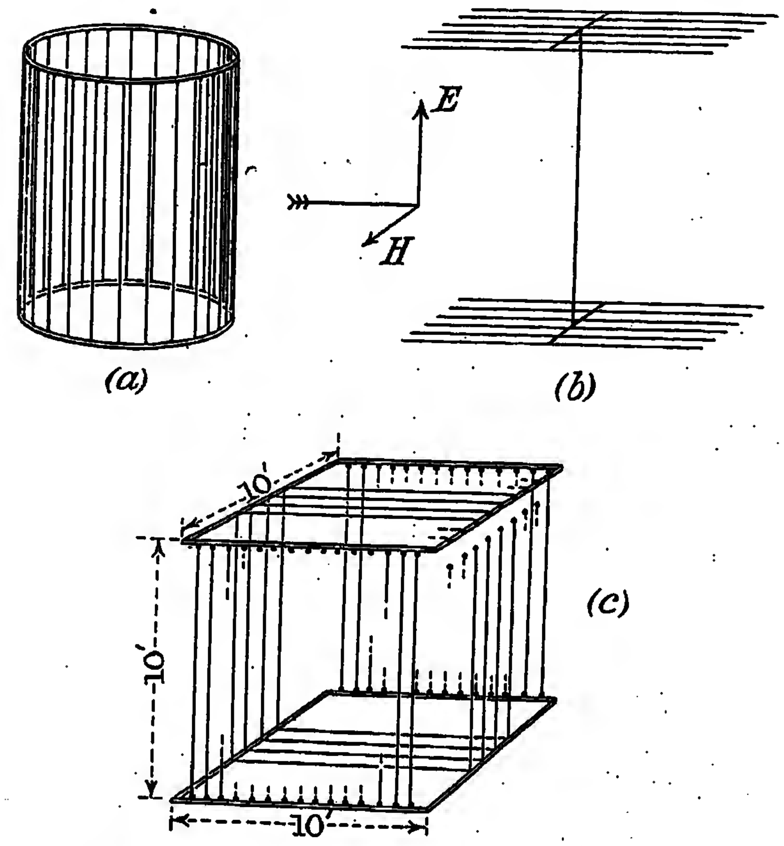

FIG. 11.—Screens which reduce electric field of waves without reducing magnetic field.

(a) Straight wire screen.
(b) "Condenser" screen.
(c) Combination of (a) and (b).

parallel [Fig. 10 (a)]. The signal strength will now depend on the P.D. (V_a) across the condenser C_2, which will be proportional to the antenna or vertical E.M.F. (E_a) induced in the system, which, in its turn, is proportional to the resultant electric field intensity E in the region in which the apparatus is situated.

To make the measurement, the procedure is first, with the apparatus unscreened, to adjust the compensating condensers with the switch in position (2) until the coil is free from antenna effect. The coil is then rotated until a position is found in which the signal strengths obtained on both sides of the switch are equal. The operation is then repeated with the apparatus in the screen under investigation. In order to obtain a fresh balance it will be necessary by rotation to reduce the E.M.F. induced in the coil in the same proportion as the antenna E.M.F. has been reduced by the screen. We shall then have:—

$$V_a = V_c$$

Thus, if E_1, E_2, and H_1, H_2 are the intensities of the electric and magnetic fields before and after screening, then

$$\frac{E_1}{E_2} = \frac{H_1 \cos \alpha_1}{H_2 \cos \alpha_2}$$

where α_1 and α_2 are the angles made by the coil with its maximum position in the two cases. The ratio H_1/H_2 can be determined by the method used in the preceding experiments, so that in this way it is possible to arrive at the effect of the screen on the electric field.

It is assumed that the intensity of the resultant electric field within the screen is substantially uniform throughout the region screened and that the screen does not affect the constants of the measuring apparatus.

FOURTH EXPERIMENT: EFFECT OF "CONDENSER" SCREEN ON ELECTRIC FIELD.

The method was then employed to investigate the properties of what may be called the "condenser" type of screen. This screen, which is of the type shown in Fig. 11, consisted of a number of wires 15 ft. long, spaced 6 in. apart and stretched horizontally about 1 ft. above the top of the coil. The set was placed under the centre of the screen and, near the centre point, all the wires were connected together by means of a single cross-wire, an extension of which formed the down-lead to the earth terminal of the apparatus. A switch was provided in the down-lead so that the screen could be earthed or isolated at will.

By means of this arrangement the general effect of the screen could be at once demonstrated, for on earthing

TABLE 6.

Screening Effect of "Condenser" Screen: $\lambda = 2\cdot 9$ km.

Arrangement		α_1	α_2	$E_2/E_1 \left(= \frac{\cos \alpha_2}{\cos \alpha_1}\right)$	Screening ratio	Remarks
Number of wires	Spacing					
		deg.	deg.		per cent	
29	6 in.	63·5	87·0	0·12	88	
29	1 ft.	63·5	85·0	0·20	80	
13	6 in.	63·5	84·1	0·23	77	
13	1 ft.	63·5	80·0	0·39	61	
13	1 ft.	63·5	80·0	0·39	61	Earthed copper matting under instrument and operator
7	6 in.	63·5	76·5	0·52	48	

the screen a large decrease in signal strength was observed if the apparatus was operating as an antenna [switch in position (1)], but there was no change at all if it was working as a coil receiver [switch in position (2)], thus showing that the electric field is screened while the magnetic field is not affected.

After investigating the effect of the complete screen, various alterations were made in it in order to get some comparative information as to the effect of different shapes and sizes of this type of screen. In all cases, since $H_2/H_1 = 1$, the relation $E_2/E_1 = (\cos \alpha_2)/(\cos \alpha_1)$ holds good. The results are summarized in Table 6. It will be seen that the greatest screening effect is obtained with the screen of largest dimensions, and closest spacing when the electric field is reduced to approximately 1/10th its normal value. On increasing the spacing, or decreasing the dimensions, the effect of the screen is distinctly less.

By making the spacing of the screen still less, and by increasing its dimensions, it is probable that any desired reduction of the electric field could be produced without appreciably affecting the magnetic field.

Effect of Vertical-wire Cage and Open-loop Cage.

A vertical-wire cage was now constructed similar in type to that already experimented with (see Fig. 5). It consisted of a 10-ft. cubic frame open at top and bottom and having vertical wires spaced 6 in. apart stretched over each of its sides. The wires were free at their top ends, but their lower ends were all connected together and to an earthed "mat" of wire netting forming the floor of the cage. The screen was found to have a screening ratio (electric field) of about 80 per cent, showing it to be slightly less efficient than the "condenser" type of screen previously experimented with.

A third type of screen consisting of a series of rectangular loops in parallel planes was now constructed on the same frame. This cage was made up of conductors of the type shown in Fig. 7 (*b*), i.e. the loops were not continuous but were interrupted by means of an insulator at one of their upper corners. This type of screen has already been shown to have no effect on the magnetic field of the waves, whereas for the electric field it was found to possess a screening ratio of well over 90 per cent. Thus this screen was the most efficient so far constructed. It also possesses the advantage over the condenser type, of occupying considerably less space. When a direction-finding coil was set up in this cage the minima were found to be extremely sharp, showing that, as was to be expected, "antenna" effect had been reduced to a negligible quantity.

These experiments clearly demonstrate that it is possible by the various arrangements described to screen a region from the electric field of an electromagnetic wave without reducing the magnetic field.

Use of Open-loop Cage as Anti-Antenna-effect Screen for Direction-finding Apparatus.

A cage of the type last described (open loop) has been set up at Slough as an anti-antenna-effect screen for a direction-finding set which is being employed to take accurate observations. In this case the screen has been constructed round the outside of the hut in which the set is working, this hut being raised several feet off the ground and resting on four large "shed" insulators. The framework on which the loops are mounted is a 12-ft. cube with the hut in the centre. There are two sets of 24 vertical loops spaced 6 in. apart, one set being at right angles to the other. A space of 6 in. is left between the horizontal wires of one set and those of the other. Each loop consists of a conductor bent into a square of 12-ft. side broken electrically at one corner by an insulator. Each successive loop is rotated through 90° in its own plane relative to the preceding loop, so that the gaps in the loops come at each of the four corners in turn. This rotation results in a greater symmetry of the whole structure.

This screen has now been in use for some considerable time and has proved very effective. The directional minima are very sharp, a swing of only 1° being necessary over the whole range of wave-length so far employed, viz. from 450 to 9 000 m. The presence of the cage has not reduced the signal strength or affected the accuracy of the bearings taken within it to any measurable extent.

Discussion of Experimental Results.

When a screen or any system of conductors is acted upon by electromagnetic waves, currents are set up in

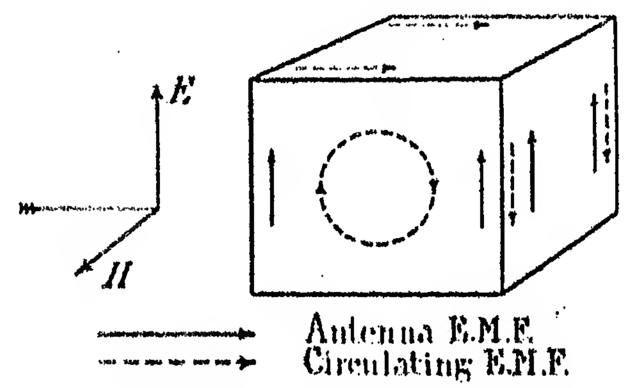

Fig. 12.—Conducting cube in path of long waves.

it which create secondary electric and magnetic induction fields in its neighbourhood and also re-radiate a certain amount of energy in the form of waves. Unless the screen is very close to the transmitter, or of dimensions comparable with that of the wave-length, this re-radiation can be entirely neglected. These last two conditions being ruled out as regards the experiments here described, it appears that in any screened region the actual field existing at any instant will be the resultant of two components: (*a*) the main field, as it would be in the absence of any screen, and (*b*), the secondary induction field due to the currents set up in the screen by the main field. Thus, a perfect screen would be one in which the secondary field was exactly equal but in the opposite direction to the main field at every point within it.

The particular phenomenon investigated by the experiments described is that of the screening of electromagnetic waves by a conductor of linear dimensions small compared with the length of the waves. Consider, therefore, a small block of copper placed in the path of long radio waves (see Fig. 12). Looking at the case

from the point of view of the electrical field of the waves, it is clear that, first, the block will behave as a short, squat, vertical antenna; that is to say, vertical oscillating currents will flow through or over its sides between its top and bottom faces; and secondly, owing to the phase difference of the part of the field arriving at the block and the part of the field leaving the block, circulating currents will be set up around the bounding surfaces of the block about an axis perpendicular to the direction of the waves and to that of the electric field. The first effect may be termed the "antenna" effect, the second the "closed loop" effect. Exactly the same result would, of course, be arrived at by considering the problem from the point of view of the magnetic field; in fact, it is perhaps rather simpler to consider the circulating currents in terms of the magnetic field, and the "antenna" currents in terms of the electric field.

On altering the shape of the conducting block, the relative importance of the two effects will be varied. If it be made very elongated, the "antenna" effect becomes of greater importance than the "circulating" effect, while the reverse holds if it be made short and broad. The consideration of two special cases actually dealt with in the experiments will, at this stage, most clearly illustrate the respective parts which these two effects may play in screening.

The case of straight wires.—The first case is that of a short and straight wire placed parallel to the electric force. Here the "antenna" effect is of sole importance, any circulating currents in the thickness of the wire being negligible. Under the conditions prevailing in the experiment, i.e. with the natural frequency of the wire large compared with that of the waves, the secondary electric field set up as a result of the "antenna" current will be 180° out of phase with the main field and, at points near the centre of the wire, in opposition to it. Such a wire will therefore reduce the electric field but not the magnetic field, since there are no circulating currents to produce a counter magnetic field, and any magnetic field resulting from the antenna currents will be 90° out of phase with the main magnetic field and of an entirely secondary order.

This argument may clearly be extended to the case of a number of parallel wires arranged as a screen or cage [see Fig. 11 (*a*)] and also to that of two horizontal plates connected by a wire [see Fig. 11 (*b*)] or to that of an earthed system of horizontal wires forming what may be termed a "condenser" screen, provided of course that the assumptions made above with regard to the natural frequency of the screen still hold good.

The experiments carried out with such screens are in complete agreement with these conclusions. The negative effect of a screen of straight wires on the magnetic field is demonstrated effectively on page 253, while the experiments on page 258 carried out as a result of this analysis illustrate the effect of this class of screen in reducing the electric field and show how it is possible to construct a cage which will reduce the electric force to a very small fraction of its normal value without appreciably altering the magnetic field. Again, it will be found that the above reasoning satisfactorily explains the experiment with the loop with screened sides (see page 250).

As further evidence supporting the conclusions, the experimental work of Blatterman * must be mentioned. In 1919 he succeeded in reducing "antenna" effect in a direction-finding set by means of a "grounded electrostatic shield" very similar to the type employed in the experiment described above. Blatterman, however, does not give the above explanation for the phenomenon, but ascribes it to the screen bringing about "a more symmetrical system electrically," from which it appears that he considers it to be acting in the manner of a compensating condenser. The fact that by regarding the phenomena as one of screening it has been possible greatly to improve the design of a shield as used for Blatterman's purpose, is, however, a strong argument in support of the correctness of this way of looking at it.

Case of closed loops.—The second case is that of one or more closed conducting loops. Let such a loop be placed with its plane parallel to the electric force and perpendicular to the magnetic force in the wave. It will be assumed that although the waves are long compared with the diameter of the loop, the frequency is still so high that its reactance is large compared with its resistance. It is then clear that the secondary magnetic field produced by the currents circulating in the loop will, at points inside the circumference, be almost exactly 180° out of phase with the main magnetic field, so that the resultant field will be less than the main field and the loop should screen its interior as regards the magnetic field of the waves.

Thus, if a be the radius of the loop, L its inductance, and if H_1, H_s and H_2 be the value of the main, secondary and resultant magnetic fields respectively, we have at the centre :—

$$H_s = \frac{2\pi I}{a}$$

where I is the circulating current.

Now $I = E/(\omega L)$ (neglecting R^2 in comparison with ω^2L^2) and $E = \pi a^2\omega H_1$, therefore

$$H_s = \frac{2\pi^2 a}{L} H_1$$

Now one of the single loops used in the final experiment is approximately equivalent to a ring of 1-metre radius, for which, by calculation, $L = 10^4$ cm (about). Hence, for this loop,

$$H_s = \frac{2\pi^2 10^2}{10^4} H_1$$
$$= 0 \cdot 2H_1$$

but $H_2 = H_1 - H_s$ (assuming H_s to be 180° out of phase with H_1) $= 0 \cdot 8H_1$.

The actual experimental result (page 254) was $H_2/H_1 = 81$ per cent, so that the agreement is good.

Extension to other cases.—If a number of parallel loops be placed parallel to and co-axially with the loop above considered, the screening effect at the centre of the

* A. S. Blatterman: *Journal of the Franklin Institute*, 1919, vol. 188, p. 338.

system will naturally become greater, as the experiment showed, since each loop will now contribute something to the total result.

If the loops are close together (though still isolated from each other) and sufficient in number to form a long cylinder, the secondary field at points not near the ends will be substantially uniform over the whole cross-section, and since the total secondary flux across such a section must be equal to the main flux (neglecting resistance) it follows that the screening ratio will be very nearly 100 per cent. The case of a solid cylinder has now been arrived at. It differs from the above, however, in one respect, for, whereas the series of loops will not screen at all if the magnetic field is perpendicular to their axis, a solid cylinder will screen even in this case, since paths for circulating currents exist in planes parallel to the axis.

All the above points relating to loops and cylinders were demonstrated by the various experiments already described.

The simplest method of making the screening independent of the direction of the magnetic field is to arrange three sets of loops in three planes mutually at right angles. If in such a screen as this the points of intersection of the wires of the loops are imagined to be electrically connected, the case of the wire-netting cage has been arrived at. Screening phenomena in wire-netting cages must therefore be of the same nature as those occurring with loops. A decrease in the size of the mesh is equivalent to an increase in the number of loops and should accordingly increase the screening effect, as demonstrated in the experiment, while at the same time making the resultant field more uniform throughout the region screened.

Finally, if the mesh is indefinitely reduced, the case of a completely closed box is arrived at. Since we know that in such a box the screening ratio may be made to approach as nearly as we like to 100 per cent, we may conclude that, as the theory would indicate, the secondary field within is perfectly uniformly distributed and exactly equal to the main field. If, however, the sides of the box were made very thin or of bad conductivity, the secondary field would be weaker than the main field and a considerable resultant field might exist within.

With regard to the effect of gaps or holes in screening boxes or cages, theory would appear to indicate that a long slit in a transverse direction to the circulating currents set up would cause a considerable reduction of its screening properties, but that if the slit lay along the path of the currents its effect would be negligible. The results of one observation confirmed this conclusion [see Table 5, line (10)].

The effect of wave-length variation on screening ratio disclosed in the case of wire-netting screens (see Fig. 9), which shows a slight increase of screening ratio with wave-length according apparently to a straight-line law, undoubtedly indicates that, as would be expected, the secondary field distribution varies with the frequency. This is no doubt brought about by the redistribution of current, which will tend to confine itself more and more to the outside surface of the cage at higher frequencies.

Antenna effect in loops.—So far, however, we have considered only the "circulating" effect in the loops and have as yet paid no attention to the "antenna" effect. The "circulating" currents, as we have seen, produce a magnetic field which opposes and therefore reduces the main magnetic field, but these currents cannot affect the main *electric* field of the wave, since any electric field associated with the circulating currents will be 90° out of phase with the main electric field, and of an entirely secondary order. It is here, however, that "antenna" currents are effective, producing under these particular conditions of dimensions and frequency a secondary electric field tending to oppose the main field within the loop. The extent to which the electric field is in this way reduced was not investigated by experiment in the case of closed loops, but this could be done if necessary by employing the method described on page 257.

Screening of magnetic field but not electric field.—Thus we see that a closed loop screens both the

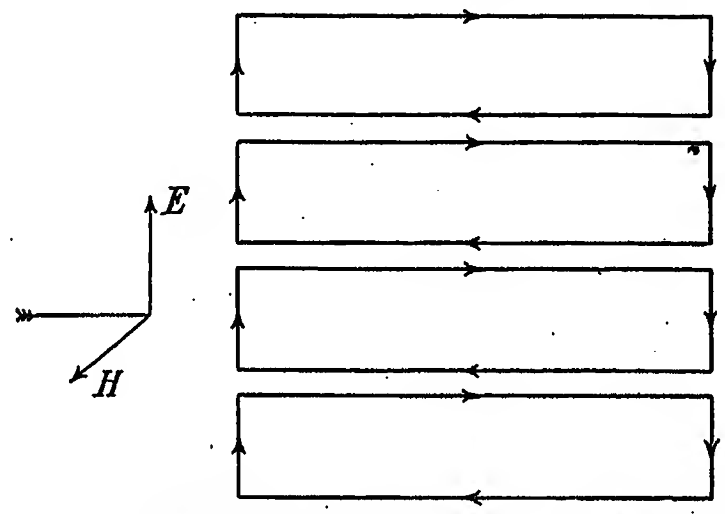

FIG. 13.—Arrangement for screening magnetic field without affecting electric field.

electric and magnetic field within it, whereas a straight wire or open loop screens the electric field only. It was suggested to the author by Professor Howe that the converse of this could be achieved by constructing a screen of loops arranged in the manner shown in Fig. 13, i.e. a series of elongated hoops of small height fixed in one plane and separated by small gaps. An examination of the direction of the arrows representing the current in the figure will show that the currents in any two adjacent horizontal members will have mutually opposing effects at points not close to them, thus leaving the current in the boundary conductors as the only effective ones. This arrangement should therefore act like a single-turn loop of area equal to that of the whole system as far as the secondary magnetic field is concerned, whereas it should produce little or no secondary electric field at such points since the path for antenna currents is broken. Such a system should therefore screen the magnetic field but not the electric field.

This arrangement was accordingly set up and tested. The overall area of the system was 10 ft. square and there were four loops, the size of each loop being 10 ft. long by 2 ft. high, with 6 in. between the loops. Its properties were found to be as predicted, for at a point 2 ft. from the centre of the screen the electric field

($\lambda = 3$ km) was not apparently affected, while the magnetic field was reduced by about the same amount as was obtained with the single loop in the first experiment. When, however, the loops were all connected together, the electric field was reduced considerably (by about 20 per cent).

A more efficient screen with this property could be made, if required, by constructing a series of screens of the above type in parallel planes.

General Conclusions.

The following conclusions may be drawn as a result of the experiments described in the paper.

(1) Since the problem of screening a given region from the magnetic field of a wave differs distinctly from that of screening the electric field, the design of a screen must differ according to whether it is desired to screen one kind of field only or both equally.

(2) The effect of a screen on the *magnetic* field of electromagnetic waves depends mainly on the existence of closed conducting paths surrounding the screened region. Any given path, however, screens only that component of the magnetic field which is perpendicular to its plane, so that it is possible to obtain a "directional" screen by an arrangement of single loops in parallel planes. The main point in designing an efficient screening box will therefore be to ensure that three such good conducting paths exist in three planes mutually at right angles. A metallic box with electrically good joints at all eight edges fulfils this condition very well. For such a box, a thickness of copper of less than 1 mm will reduce the field within to a fraction of 1 per cent of its normal value. If, however, the box is open at the top or at one side it will only screen efficiently magnetic fields perpendicular to the open face. A box with an ill-fitting lid will, of course, behave in the same manner however thick it may be. If there are a limited number of gaps or holes in the sides for control purposes, the parts of the interior at distances from such holes, large compared with their dimensions, will not be appreciably affected by the holes.

(3) A screening box or cage will be effective as regards the *electric* field of a wave, provided that each face is connected to its opposite face by a good conducting path.

(4) To protect a region from the electric field of a wave without affecting the magnetic field, the individual conductors in the screen must be "open" circuits, e.g. straight, insulated wires or open loops.

(5) To protect a region from the magnetic field of a wave without affecting the electric field, the screen must consist of a series of small loops arranged so that there is no electrical continuity in the direction of the electric field.

(6) It is extremely difficult to get a perfect screen. Even the smallest gaps allow a detectable amount of energy to enter, while joints or seams of low conductivity have the same effect. These facts were demonstrated by the experiments in the tank and with the loop with screened sides. On the other hand, even such coarse material as 1-inch or 2-inch mesh wire netting has a very considerable screening effect, namely, of the order of 95 per cent and 90 per cent. This value for such cages is practically constant over the greater portion of the range of commercial wave-lengths, decreasing slightly, however, with increase of wave-length according apparently to a straight-line law.

(7) A direction-finding coil enclosed in a screen of the type mentioned in (4) above (see Fig. 11) is rendered almost completely free from antenna effect, it being possible by suitably constructing the screen to ensure that such residual effect as may remain shall be quite inappreciable.

These investigations were carried out for the Radio Research Board under the direction of the Sub-Committee on Directional Wireless, the members of this Sub-Committee being as follows:—Mr. F. E. Smith, C.B.E., F.R.S. (*Chairman*); Mr. F. W. Davey; Mr. C. E. Horton, B.A.; Captain C. T. Hughes, M.C., R.E.; Dr. J. Robinson, M.B.E.; Dr. C. C. Simpson, F.R.S.; Dr. R. L. Smith-Rose; and Mr. O. F. Brown, M.A., B.Sc. (*Secretary*).

In conclusion, the author wishes gratefully to acknowledge the many valuable suggestions and general encouragement given to him by Dr. Smith-Rose throughout the work.

Discussion before the Wireless Section, 2 January, 1924.

Dr. R. L. Smith-Rose: The author and I were continually meeting this problem of screening in connection with our more general work on the propagation of waves, and, on reference to the literature on the subject, very contradictory ideas and statements were brought to light. One writer recommended a gauze screen to accomplish the same object which another writer insisted could only be obtained by using very thick iron and welded joints; in other cases screen boxes have been constructed of alternate sheets of copper and iron, with the idea of screening first the magnetic field and then the electric field. One of the causes that have given rise to this confused thought has been the misapplication of the term "Faraday cage." The original Faraday cage was, of course, only applicable to electrostatic conditions, and in such a case I think that the screening is practically perfect, even though the cage be constructed of wire mesh or gauze or perforated sheet. Immediately the electric field is alternating or varying, however, the electrostatic conditions have to be modified and the currents which flow in the screen itself have to be taken into account, in which case I think the term "Faraday cage" becomes a misnomer. The problem was first encountered in connection with the requirements of the extension of the direction-finding systems to continuous-wave working. It was required in that case to construct a local oscillator and so screen that oscillator that no stray field intersected the rotating loops used in the direction-finder. The stray fields were giving rise to false zeros,

and therefore wrong bearings. As a result of a great number of experiments carried out on the screening of such an oscillator, it was shown that solid iron sheet was considerably better than other metals, e.g. copper, and that the effect of large gaps and holes in the sheet, which are unavoidable if the oscillator is to be made of practical use, could be largely obviated by allowing a considerable overlap in the lid of the box and making tight contact all round the periphery of the box. The experiments described in the paper show that what is required to screen a space is to obtain a large ratio of reactance to resistance of the metal employed for the box, and copper would appear to be the best metal for that purpose. There appears, therefore, to be a slight contradiction in the results obtained in connection with the screening of a local oscillator and the screening of a space from an incoming wave. A little consideration of the details and conditions prevailing in the two cases shows, however, where the discrepancy arises. So long as the magnetic field has an air path inside the screening box, then the largest ratio of reactance to resistance is obtained by the use of copper; but if the path of the magnetic field lies for any appreciable length through metal, then iron has an advantage over copper, because advantage can be taken of the permeability of that metal. In the case of the screening of a space from a wave, the magnetic field is uniform over the whole portion of the screen, and thus, by arranging a number of conducting loops in planes at right angles to the direction of the magnetic field, one can obtain the necessary conditions. In the case of the screening of a source of oscillations, however, the direction and intensity of the magnetic field vary greatly from point to point over the surface which will be occupied by the screen; in fact, it is quite possible that inside the box the resulting primary field through the box may be zero. In this case the screening that is to be accomplished is rather in the form of local screening, which can be obtained by the eddy currents set up in the sheets of the metal. These eddy currents actually flow within the thickness of the metal, so that the path of the secondary magnetic field is a metal path. The penetration of the magnetic field in that case is given by the common skin-effect formula. Some of the author's work has a valuable application in sharpening up the minimum obtained on an ordinary rotating-frame coil, whether used for direction-finding or for the purpose of diminishing interference. The minimum obtainable on such a direction-finding set is not quite as sharp as that obtainable by the use of a compensating condenser, but it is possible that the zeros obtained by a compensating condenser are false balance positions. In any case the minimum has been reduced with this screen to as small a magnitude as is sufficient for practical purposes at present, and greater accuracy is not warranted because of other effects which occur in direction-finding.

Dr. J. Robinson: Most people who have made experiments with direction-finding have from time to time found the necessity for screening for various purposes. Some other aspects have not been definitely referred to in the paper, such as the elimination of magneto noise on aeroplanes and the elimination of noises produced by neighbouring electric motors. It will be interesting to know whether the author has found that his methods have any influence on the latter form of disturbance. The paper at first sight appears to give the impression that it is possible to eliminate the magnetic component of electromagnetic waves without touching the electric component, and vice versa. Such a statement would appear to be in direct contradiction to Maxwell's theory. Closer examination will, however, show that there is no intention to upset Maxwell's theory, for practice in direction-finding has led to the general impression that certain effects which one obtains with loops are the results of the magnetic fields, and other effects are the results of electric fields, whereas it is fundamental that any of the effects produced in a loop can be explained from either the magnetic or the electric standpoint.

Mr. L. Bainbridge-Bell: The company with which I am associated has for some time been fitting direction-finding sets in ships, and it may be of interest to give some particulars of the screens used for protecting the rotating coils from antenna effect. These screens are fixed to the inside of a watertight box, which protects the coils, and are very similar to that shown in Fig. 11 (*c*). The screen on each side of the box is formed by 20 vertical wires (20 S.W.G.) about 2 in. apart. The lower ends of these are connected to a horizontal wire running round the four sides of the box, but broken at one point to avoid a closed loop. A similar screen is placed inside the top of the box and connected to one of the vertical wires. The horizontal wire is earthed. In order to ensure symmetry in the down-leads from the coils, a transformer is placed between the coils and the first valve of the amplifier. It is of special construction, the primary being split and the tuning condenser being connected between the two halves. In reply to Dr. Robinson, who asks whether a screen is effective in cutting out disturbances from neighbouring electrical machinery, I should like to say that I have not found that it reduces these disturbances at all. This, I think, is only to be expected, as the electrical machinery appears to "shock-excite" the conductors near the direction-finding coils, which radiate waves that affect the coils somewhat as do those emanating from distant wireless stations.

Captain C. T. Hughes: I think that Dr. Smith-Rose, in drawing a comparison between the effectiveness of a screen such as that described by the author and that obtained with compensator methods, has overlooked the extreme convenience of using a compensator on small portable installations. I should like to ask the author whether it is really necessary to have an outside construction quite independent of the hut. Purely from the point of view of ease of erection, it would be a very much more convenient arrangement to rig up a screen on the walls inside the hut.

Admiral Sir H. B. Jackson: Has the author any idea how large or how small a screen will be efficient for the ordinary direction-finder 4 ft. square? In other words, would an 8-ft. cube be equally as efficient as a 20-ft. or a 50-ft. cube if the wires were spaced at the same angular distance from the centre?

Major A. G. Lee: The author's explanation of the

action of the screen, viz. that it produces a counter field 180° out of phase with the main field, and therefore cancels out the main field, appears to be very sound. Has he ever considered the effect of a screen in the case where a field arrives tilted, which sometimes happens? That is to say, does the screen work effectively in this case, or does it exhibit any tendency to exaggerate the errors due to the tilted wave-front?

Mr. R. H. Barfield (*in reply*): I agree with Dr. Smith-Rose that the problem of preventing a high-frequency electric field from entering a small enclosed space is quite different from that of preventing the energy of a local source contained in that space from escaping. As I have not investigated the latter problem, I am unable to give any information to Dr. Robinson on the screening of motors and magnetos.

I certainly believe that, as Dr. Robinson says, there is no action attributable to the magnetic field of the wave which cannot also be explained in terms of the electric field, but I think he will agree that certain phenomena are much more simply explained in terms of one kind of field than of the other. This, I think, applies in particular to the case of the loop with screened sides, and to the screening action of the straight-wire type of screen described in the paper.

It is interesting to learn from Mr. Bainbridge-Bell that the development of the Blatterman screen has been carried on by others than myself and to find that the form at which they have finally arrived is very similar to that which has been found most successful at Slough. I would, however, regard as an unnecessary precaution the provision of a "break" in the horizontal loop which Mr. Bainbridge-Bell describes, since such a loop, whether open or closed, can have no screening effect whatever on the coils of the direction-finding set to the planes of which it is perpendicular.

As Captain Hughes suggests, an anti-antenna-effect screen erected within the direction-finder hut should be quite as effective as one outside. The screen should, however, be large enough to contain the operator, and the spacing between the wires should be small compared with the distance of any part of the apparatus from the side of the cage.

In reply to Admiral Jackson, I should say that provided the above precautions are taken in its construction the effectiveness of a screen will be independent of its size.

In reply to Major Lee, the cage now in use at Slough which I have described in the paper is so constructed that its screening effect on the electric field is independent of the direction of that field in space, while, on the other hand, whatever the direction of the magnetic field it will remain unaffected by the screen.

DISCUSSION ON "LOUD-SPEAKERS FOR WIRELESS AND OTHER PURPOSES,"

WITH INTRODUCTORY PAPERS BY

(*Joint Meetings of* The Institution *and the* Physical Society of London, 29*th November*, 1923, *and* 14*th February*, 1924.)

GENERAL PRINCIPLES INVOLVED IN THE ACCURATE REPRODUCTION OF SOUND BY MEANS OF A LOUD-SPEAKER.

By Professor A. O. Rankine, D.Sc.

The task of opening this discussion is not an easy one. My difficulty arises, no doubt, largely from the mistake of supposing that a mere lively interest in the subject constitutes a sufficient qualification for making the introductory remarks. But I have also an uneasy feeling that there may be in relation to loud-speaking devices many important discoveries which continue to be withheld from public knowledge because of their commercial value. Consequently I may say things which might immediately be proved from practice to be wrong, if only everyone would reveal what he knows. The problem is, in fact, one in which practice has outstripped theory, as in the beginnings of aerial flight. A sudden great public demand has had to be met, and the problem has approached solution, so far as we know, by trial-and-error methods and without much appeal to the theorist. But few would deny that the products leave room for considerable improvement, except, perhaps, those responsible for advertisements (frequently to be seen) in which certain loud-speakers are described as "perfect in tone" and "absolutely faithful in reproduction." The real position seems to be that there is rather wide-spread discontent with the loud-speaking devices which are in use; and the purpose of this discussion is, I take it, to endeavour to identify the defects and suggest means for their elimination.

I think that the most useful thing I can do—in fact the only thing I am able to do—is to present certain considerations, mainly theoretical, which will be admitted to have an important bearing on the question before us. Some of them are rather obvious, and have probably already been taken into account by manufacturers. But few who have worked in acoustics have not, at some time or other, been faced with apparent contradictions between theory and practice; it is wise, therefore, sometimes to pause and reconsider what is fundamental and true. First of all, what is the practical problem? We wish to procure at one place the emission of sounds which are a sufficiently faithful copy of those originating at another place. It is not enough that the imitation should be agreeable; we do not want, to take an extreme example, a piccolo played very badly to reappear as a performance on a bassoon completely above reproach. Whatever the original sounds are, we want the reproduction to be like them. Besides this—and it is here that apparently the chief difficulty presents itself—we require that the reproduced sounds should be of considerable intensity. Although there is no need to specify this intensity precisely, we may, perhaps, for the purpose of argument, say that the sounds emerging from a loud-speaking device (if it is to deserve the name) should be at least as loud as those emitted by the original source. In other words, the ideal loud-speaker would be a secondary source in every acoustic respect equivalent to the primary source, whether speaker, singer or musical instrument. Put into the language of mechanics this means that the vibratory movements of the air at any specified distance from the loud-speaker should be identical with those which would occur if the original source were substituted for the loud-speaker. This statement of the case, it is true, leaves out of account the important question of the spacial distribution of a large sound source such as an orchestra. It is not easy to see how any practicable loud-speaking device could imitate this effect. But this aspect of the subject has been deliberately ruled out of the discussion by its limitation to the field of reproduction, and I shall not break the rules in this respect. Nor shall I enter into psychological considerations further than to remark that it is conceivable—perhaps probable—that perfect fidelity of sound reproduction alone may never lead to complete satisfaction by compensating for missing factors. It is at least arguable that visual conditions are not entirely unimportant; the sight of the lips or of the instrument manipulation may be needed to complete the effect.

The point at which our inquiry begins is, as I have already said, not earlier than the stage in which there

are at our disposal, in electrical transmission at any rate, certain electrical fluctuations corresponding to the original sounds. The question is how to manipulate these electrical vibrations so as to procure a satisfactory copy of them in aerial vibrations of large amplitude. For I think that for present purposes we may take it that already we have available sufficiently good reproduction if we are content with feeble intensity. There is, in my view, little cause for complaint in the behaviour of good-quality telephone receivers applied close to the ear and emitting sounds then just comfortably audible. Again, it will probably be generally admitted as true that the quality of the sounds given out even from a loud-speaker may be improved by reducing the output attempted. It is when large emission intensity is required that the distortion becomes too marked even for non-critical ears. I am no believer in the practical necessity of attaining the ideal case in which the aerial vibrations are copies, perfect in every detail of frequency, amplitude and phase, of those which gave rise to them. My own small experience has led me to the view that considerable latitude in this respect is permissible. On theoretical grounds, too, it would appear that to procure reproduction absolutely perfect in the physical sense, as distinct from the acoustic, is not possible, having regard to the variety of transformations which are in practice necessary. But there must be a limit for this physiological latitude, and there is evidently a danger, in seeking loudness, of departing too much from similarity. The various stages in the process each give rise to the possibility of distortion, and the effect is presumably cumulative; thus each stage requires careful consideration.

Broadly speaking, there are, from the point at which the field of discussion opens, three operations. There is first the amplification of the electrical fluctuations; in the second place there is the process whereby the current excites corresponding variations of air pressure; and thirdly, we have the treatment of the aerial vibrations after they have been created. With regard to the first I am not able to speak at any length; it is a question of using one fluctuating current to impress its own features on another of greater power, usually in several successive stages. Most of us who have occasion to use thermionic amplifiers are aware that the later stages become more and more difficult, and we are fortunate to have the prospect of hearing later from Professor Fortescue what ought to be done. Perhaps he will be able to tell us also what are the limits of this type of amplification from the point of view of the subject in hand.

Our second question—that of the transformation of a portion of the electrical energy into sound energy—is so broad that it is difficult to choose a point of departure. Each mode of transformation, according to whether it is by electromagnetic, electrostatic or thermal means—to mention only some of the better known—provides a different field for investigation; and it would be impossible for me in the time at my disposal, even if I had the knowledge, to deal with them. In all cases, however, it is a question of forced vibrations, and I propose to make some general remarks on this subject which inevitably have a bearing on the problems of transmitting as well as those of receiving. I cannot do better than take as a text two quotations from Lamb's "Dynamical Theory of Sound."

"The reason for the pre-eminent position which the simple harmonic type occupies in Mechanics is that it is the only type which retains its character absolutely unchanged whenever it is transmitted from one system to another,"

and later, in elaboration of this point, after determining the forced oscillation under the action of a force composite only in the sense that it requires more than one different simple harmonic term for its representation,

"This is an illustration of the remark made in par. 1 that the simple harmonic type is the only one which is unaltered in character when it is transmitted, the character of the *composite* vibration . . . being different from that of the generating force. In particular if one of the imposed speeds p_1, p_2 . . . be nearly coincident with the natural speed n, the corresponding element in the forced vibration may greatly predominate over the rest."

Thus we cannot reproduce sounds in general with complete precision; all we can do is to take steps to avoid too great changes of character in the often very complicated vibrations which we sometimes dissect for convenience into harmonic components. And the quotation just given directs attention to one of the chief dangers, namely, resonance. In aiming at loudness there is, no doubt, a temptation to resort to resonance as a means to that end. In the majority of telephone diaphragms, for example, there are natural frequencies where they ought not to be, i.e. within the range of frequencies of the sounds used, and the corresponding components of the sounds inevitably get preferential treatment. This, of course, can be rectified to some extent by damping the diaphragm, a process which diminishes the selectivity of the resonance by broadening the range of frequencies over which it occurs. But inevitably the general sensitivity is thereby reduced, and it seems to be at least worthy of greater consideration whether, especially in view of the fact that in operating loud-speakers it is usually possible to detect one or more diaphragm notes, advantages might not accrue from plans alternative to permitting resonance and only partially suppressing it.

There are two obvious ways of proceeding. One is to increase the natural frequencies of the mechanism to values above the upper limit of audibility, or at least as far in that direction as may be practicable. The other is to choose mechanisms of very low natural frequencies, so that none but the relatively high overtones—which are not very liable to be excited—reach the lower limit of audibility. On theoretical grounds the former method is to be preferred, since it would give displacement components more closely corresponding to the exciting force. Where loudness is not important this procedure has, I believe, proved very satisfactory; it remains to be seen whether the sensitivity necessary for loud-speakers is attainable under like conditions. Perhaps others with more knowledge of the mechanical

properties of, for example, a diaphragm, will be able to say what are the prospects in this direction.

The other alternative, that of using mechanisms of very low, i.e. nearly zero, natural frequencies, is also worthy of continued consideration as possessing, at any rate, advantages over more resonant arrangements. One device of this type is to be exhibited at this meeting, and there is another, of which I heard not long ago, which presents certain features novel enough to be worth mentioning. It is attributed to Siemens Halske, and is said to consist of a strip of thin metal foil suspended between the poles of an electro-magnet, as in the Einthoven galvanometer. The plane of the foil is parallel to the magnetic field, and the incoming telephonic current, doubtless properly transformed to suit the arrangement, flows through the foil. This responds by mechanical movements perpendicular to its plane, and is the equivalent of the ordinary telephone diaphragm. Its fundamental natural period is 2 seconds, or thereabouts, and it is reported to operate efficiently without a horn. I mention this instrument for the purpose also of directing attention to the fact that the diaphragm (i.e. the foil) suffers no transverse forces except those due to the telephonic currents. In this respect it differs rather fundamentally from the ordinary telephone receiver in which the diaphragm, or reed, is actuated by comparatively small increments and decrements of an attractive force of large magnitude, which is present in order that the sensitive part of the magnetization curve may be utilized. Under these conditions a really sensitive diaphragm, i.e. one which at its centre responds with large displacement to the operation of a small force, seems to be ruled out, for it would be pulled over permanently into contact with the magnet poles. The modification of the system so that the diaphragm experiences no average force, as, for example, in the gramophone diaphragm, might lead to valuable results.

It is difficult to choose points for consideration from the many that present themselves. I will content myself with mentioning one more in this part of the argument, namely, the question of exciting forced vibrations in the air by means of an intermediate mechanism, a diaphragm being typical. It is said that in ordinary telephony only a very small fraction of the electrical energy received is converted into sound energy. In the pursuit of intensity of reproduction there appear at first sight to be grounds for high expectations in this direction, if only we could increase largely that proportion. I venture to suggest that it may not be wise to follow this line too far, otherwise complications arising from reaction may appear. Our forced vibration should presumably not be sufficiently energetic to be capable of altering appreciably the character of the forcing vibration. This consideration applies both to the current-diaphragm system and to the diaphragm-air system, if we have so to subdivide the process. I have sometimes wondered whether, in this latter case, a departure from the above condition may be involved by using a horn in conjunction with a diaphragm. With a horn there is an undoubted considerable increase in sound output; it is not merely a re-distribution of the sound in a particular direction. Is it not possible that the horn increases too much the amount of energy transferred by the diaphragm to the air, and thereby, quite apart from the well-recognized horn resonance, brings about distortion ?

I have only a few remarks to make with regard to the third subdivision, that is, the treatment of the aerial vibrations after they have been developed. Of horns I will say no more than that they ought, if at all possible, to be dispensed with, possibly for the reason just mentioned, more certainly because of their resonant character. Of course, they may have their uses in this respect if, after all, we have to rely on resonance for intensity, and to adopt the plan of multiplying resonances so as to cover the range of frequencies used in transmission, thus making the best of a bad job. But the ideal sound radiator would be a spherical one which in some way could be excited by the electrical vibrations so as to impart to the neighbouring air symmetrical fluctuations of pressure of large enough amplitude. I am sorry to say that I have no practical suggestions to make on this basis.

A problem of importance is that of the conditions of listening to a loud-speaker, as, indeed, it is also in listening to a live speaker. It seems reasonable to suppose that in either case ideal listening would consist of hearing speech, at any rate, by the direct effect alone, without any reverberation or echo. For this we should have to damp out all room reflections both at the sending and the receiving stations. This is, in effect, frequently done in broadcasting, if we limit the case to that of listening on receivers applied close to the ear. But a considerable proportion of listeners appear to be asking for echo effects. Although I do not agree with them I can admit the argument, more particularly in relation to music as opposed to speech, that the custom of listening in a hall has led some to prefer the admixture of a certain amount of reverberation. No doubt Mr. Sutherland will deal with this and similar questions. All I would point out now is that in practical circumstances, if we admit the desirability of appropriate "room effect," as it is sometimes called, we must recognize that the problem is different according to the mode of listening, whether with head-receivers or with a loud-speaker. With the former the echo effect, if wanted, must be imparted at the transmitting station; with the latter it is liable to develop in the listening room also. Doubting as I do the value of even one system of echoes, I cannot be expected to tolerate two different ones superimposed, such as would arise, in the absence of suitable precautions, in a room or hall in which was operating a loud-speaker emitting sounds already bearing an echo impress. My submission is that for loud-speakers, as a general rule, echoes and reverberation should be eliminated at one end at least. For broadcast opera, for example, where transmission already unavoidably has the effect, the listening room should be draped much in the same way as transmitting rooms usually are.

I should like to say a few words in conclusion with regard to methods of testing results. Audition as a test of the degree of perfection of reproduction is liable to be a matter of opinion as between one person to another. From a scientific standpoint it would be

much better to adopt a plan of taking simultaneous records of a visible type both of the original sounds and their reproduced copies, and comparing them. Even if feasible, however, I am not convinced of the value of this method except as a matter of scientific interest. Unless we could attain the ideal of identical records, a degree of attainment probably quite unnecessary for present purposes, and, indeed, theoretically impossible, we could be sure of nothing. After all, the problem is to deceive our auditory mechanisms by offering imitations; a listening comparison therefore constitutes the most direct test. It ought, of course, to be as nearly as possible a direct comparison; the original and the reproduced sounds ought to be capable of being heard not, perhaps, simultaneously, but at least alternately at frequent intervals. Our problem will be solved when the inventor is able to deceive the most critical ear, so that its owner does not know whether he is listening to the original or to the copy. It remains to be settled who is the severest critic. Those of us who have heard his recent lectures, and know of his almost uncanny faculty of mentally performing Fourier analyses, would probably nominate Sir Richard Paget.

THEORY OF LOUD-SPEAKER DESIGN: SOME FACTORS AFFECTING FAITHFUL AND EFFICIENT REPRODUCTION.

By L. C. Pocock, B.Sc., Associate Member.

If it is assumed that properly amplified and undistorted speech voltage is available in the output circuit of a final amplifier, the problem is to procure the reproduction of speech efficiently and faithfully. The exact criteria for the reproduction of speech are better known than for music, but it is probably safe to say that a system capable of reproducing speech perfectly will give a highly satisfactory performance with music.

If V is an impressed voltage of any frequency or amplitude within the region to be amplified without distortion, and P the resulting alternating air pressure outside the system, the conditions are

$$P = AV$$

where A is an efficiency constant independent of the frequency and amplitude. It is also necessary that there shall be no asymmetric distortion, that is, any single frequency V must produce only the corresponding single frequency P. This condition is also expressed by the equation above.

Present-day electromagnetic loud-speakers are, without exception, a compromise between relatively good efficiency and good quality, such efficiency as can be secured being obtained only with the aid of mechanical resonance, which is contrary to the criterion for faithful reproduction given above. Further, although telephonic speech has generally been handled in the past as a steady-state problem, recent improvements in transmission have rendered the transient phenomena associated with consonant sounds and every change of amplitude of some importance. The reproduction of severe transients cannot be perfect in any resonant system or in any system containing mass and stiffness, even though the damping be such as to prevent any natural oscillation; the severity of transients actually encountered in speech is dependent on the damping of the vocal resonances, and information on this subject, together with like information on the auditory mechanism, might indicate the desirable degree of damping from the point of view of transient phenomena. It is clear that the use of resonance to increase the efficiency cannot be pushed too far.

Practical loud-speakers consist of a rather sharply resonant system working into an acoustic load, namely, a horn. It is not quite accurate to describe the horn as a load, because the useful work is the energy transmitted through the horn. The horn is operating in a capacity analogous both to an electrical transformer and to an electrical transmission line. The likeness to a transformer is seen in the passage of energy from the high mechanical impedance of the diaphragm to the low impedance of the open end through a coupling device, which reduces energy reflection to a minimum and aims at obtaining the greatest possible transfer of energy. The likeness to a transmission line lies in the propagation of waves across the non-uniform section of the horn; the analogy is to a non-dissipative line containing distributed inductance and capacitance, the line constants changing steadily from end to end of the line in such a way that the impedance measured at one end of the line is high, and that measured at the other end is low. Such a system would form a maximum energy coupling between two different electrical impedances.

The acoustic impedance of a horn at its small end depends a good deal on the cross-section and also varies with the solid angle and the form of the horn, but, as in the electrical analogies, the impedance is also a function of the impedance into which energy is delivered, i.e. at the open end. Another view of the acoustic impedance at the small end is to regard it as the impedance of the large end modified by the

horn through which it is measured. In general, the horn impedance also varies with frequency, and, though horns of approximately uniform impedance can be made, it is clear, from a consideration of the varying mechanical impedance of the diaphragm, that such a horn is not necessarily the best.

These are some of the factors which enter into the performance of a horn. The practical considerations are usually those of size; for indoor use the horn must not be too long, so that the problem is equivalent to attempting to obtain an electrical line of length equal to a wave-length or less and having a very much higher line impedance measured from one end than when measured from the other end. The acoustic impedance is virtually coupled to the diaphragm, so that some idea of its variations with frequency can be obtained by observing the motional impedance of the receiver. A

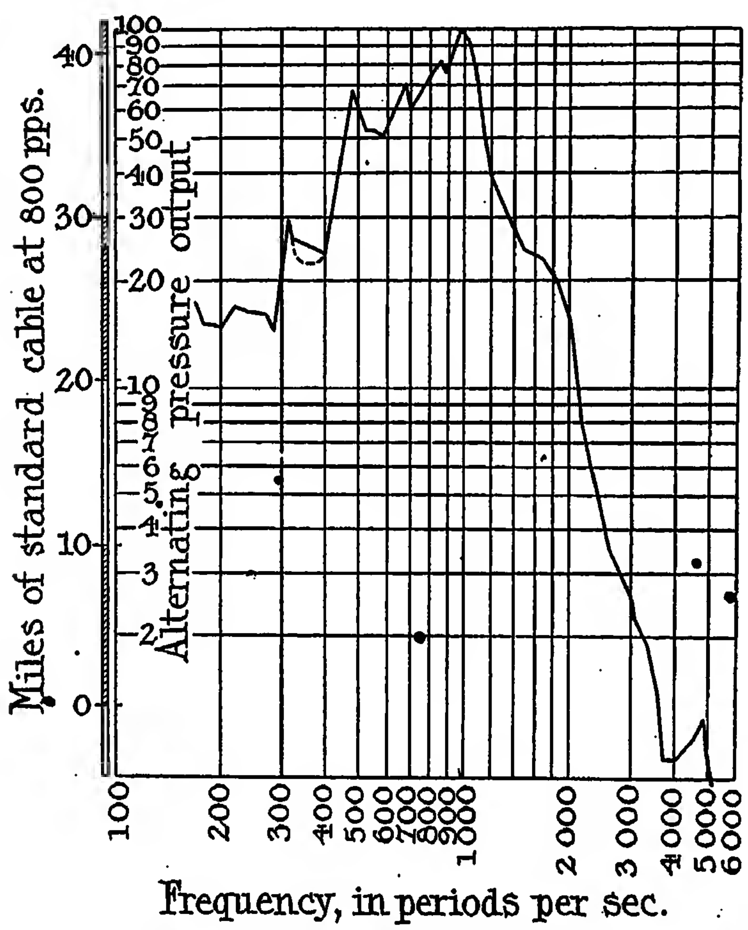

Fig. 1.—Alternating pressure output of loud-speaking receiver corrected for impedance of circuit and receiver. (Average of 5 receivers.)

large number of horns, of a size suitable for use in private houses, have been examined in this way, and resonances of varying degree have been found in all; larger horns might, however, be expected to show lesser effects.

The resonance of a receiver without horn may be such that the diaphragm vibrates with more than 50 per cent of the amplitude at resonance over a frequency region about 100 periods wide. When the horn is put in place, the diaphragm is made to do more work and the resonance is made much less sharp. The new damping coefficient cannot be simply expressed, because the resonance is no longer simple but is complicated by the coupled horn resonances.

The actual pressure variation in the air when the receiver is excited at different frequencies can be measured. Figs. 1 and 2 show the characteristics of two types of receiver. Fig. 1 is for a receiver having a flexible diaphragm driven by a small armature supported on a spring. The effective moving mass is not appreciably greater than that of the ordinary telephone receiver. The curve is an average of the results of five receivers and shows definite peaks in the lower frequency region, due to the horn. It is seen that the distortion due to these resonances is small compared with the general effect, due to the mechanical resonance of the system. This is an important point: horn distortion can be brought within reasonable limits; the receiver mechanism is often responsible for defects of tone for which the horn is blamed.

In connection with Fig. 1 it may also be stated that the perfection of reproduction is a great deal

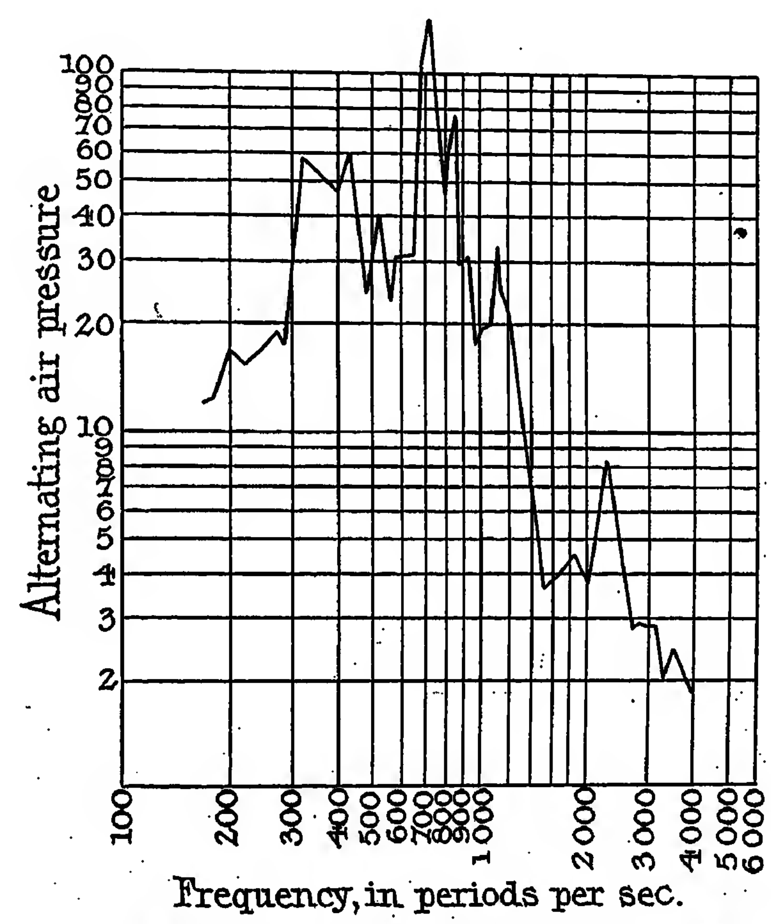

Fig. 2.—Alternating air-pressure variation with frequency for an iron-diaphragm receiver, corrected for impedance of circuit and receiver.

better than the appearance of the characteristic would suggest; the contracted logarithmic scale disguises the really rather gradual fall of the curve at the higher frequencies; even at the extreme end of the curve the highest frequency shown is reproduced with sufficient intensity to add greatly to the quality of reproduction.

Fig. 2 is the characteristic of a loud-speaker of the iron-diaphragm kind, similar in principle to the ordinary telephone receiver; in this case the curve is an average of several tests taken on the same receiver. The frequency of maximum response is seen to be a little lower than in Fig. 1, and the curve drops somewhat steeply between 1 000 and 2 000 periods per sec. (p.p.s.).

In both the above cases the receiver output is corrected for the impedance of the associated amplifier, that is, a fixed voltage is operating on the loud-speaker through a fixed resistance representative of the amplifier output impedance that would be suitable for use with the receiver considered. Since the impedance of most receivers at about 4 000 p.p.s. is two, three or more times as great as the impedance at 1 000 p.p.s., the reproduction of the higher frequencies is somewhat impaired due to this cause.

It must be recorded that Figs. 1 and 2 are relative in value, rather than absolute; in particular no correction has been applied for the variation with frequency of the absorbing power of the material used in the highly-damped chamber in which the measurements were made.

Receivers have been constructed in which large vibrating surfaces are used without a horn. It appears that the vibrating surface must be of such dimensions that there is difficulty in securing the necessary lightness of the moving parts, especially when the added mass, due to the reaction of the air, is taken into consideration. In any case, the very important distortion due to the use of mechanical resonance to obtain good efficiency remains in evidence.

With regard to the mechanical construction of an electromagnetic receiver, the ordinary construction of a telephone receiver requires considerable modification if it is to handle more than a very small amount of power and, even when so modified, there is danger of distortion due to the asymmetrical forces called into play by the passage of symmetrical currents. A receiver of the type giving the characteristic shown in Fig. 1 is capable of handling about 10 watts without asymmetrical distortion, because the armature is driven by symmetrical forces. The amplitude of vibration may be of the order of 0·01 inch.

To sum up, with present-day constructions of receivers, faithfulness in reproduction cannot be obtained beyond a certain degree without making receivers very inefficient. Reproduction can, by careful design, be made very satisfactory, but to obtain the very last degrees of perfection, e.g. by filters, enormous increases in the power amplification would be necessary to operate the receiver, in fact, valves of far higher power capacity than are used in any radio receiving sets. As it is an easy matter to obtain the present amount of amplification, it is seen that the chief interest in raising the efficiency of loud-speakers is to permit the application of quality-correcting devices, provided of course that increased efficiency is obtained without sacrifice of quality.

With regard to the overall efficiency obtained in loud-speaking receivers, it is probable that 1 per cent is a high estimate and that a few tenths of 1 per cent would generally be nearer the mark. The principal loss is iron loss, and, though eddy currents may be reduced by lamination, hysteresis still accounts for a very considerable loss on account of the high frequencies concerned. It does not seem likely that any great improvement in real efficiency can be obtained unless a magnetic material with exceptionally low hysteresis loss and good permeability is discovered. Small improvements are possible by building receivers on a larger scale and using more powerful magnets, but the necessity of making some part of the moving system of iron and of low mass makes the employment of high alternating flux density in this vital part unavoidable.

THE SOURCES OF DISTORTION IN THE AMPLIFIER.

By Professor C. L. Fortescue, M.A., Member.

(1) Scope.

In this note the output P.D. from the rectifying valve or crystal is taken as the starting-point. With an ideal amplifier this P.D. is magnified and a current of precisely the same wave-form is supplied to the loud-speaker. In many actual amplifiers, however, the wave-form is not faithfully reproduced and distortion is introduced.

(2) The Causes of Inaccurate Reproduction.

These may be put under the following headings:—

(a) Curvature of the valve characteristics.
(b) The use of intermediate circuits having more or less clearly defined natural frequencies.
(c) The unavoidable reaction effects present in most designs of note magnifiers.
(d) Unsatisfactory reproduction in the last (or output) transformer.

(3) The Effects of Curvature of the Anode Current Characteristics.

(a) *Resistance amplifier.*—The ideal resistance amplifier is as shown in Fig. 1, and consists of a valve with a non-inductive and capacityless resistance, R_a, in series with the anode and a condenser of very large capacity across the battery terminals. The valve characteristics may be conveniently plotted as a characteristic surface in terms of V_b and V_g, allowance being made for the resistance R_a.

The surface shown in Fig. 3 is the ordinary charac-

teristic surface, the lines corresponding to constant anode current, but allowance is made for a series resistance of 10 000 ohms. The fluctuations of the grid P.D. above and below the mean value may be plotted below the diagram of Fig. 3 as at G. Then, by projecting up to the line PQ, corresponding to the given value of the battery voltage, the values of the anode current can be plotted above and below the mean value at C. A reference to Fig. 3 shows that the anode current wave-form can only be an exact replica of that of the grid P.D. when the constant-current lines are equally spaced along the line PQ. Thus, if the surfaces are (which are the ones under consideration) is, however, very much greater than the resistance of the anode winding as measured by direct current. The resistance must be ascertained by a.c. bridge methods at the resonant frequency. Some transformers having a direct-current resistance of the order of 2 000 ohms are found at the resonance point to have effective resistances of 200 000 to 300 000 ohms when loaded on the secondary side with resistances corresponding to the grid resistance of the next valve. The representative characteristic surfaces must therefore be plotted for this high value of R_a and not for the d.c. resistance;

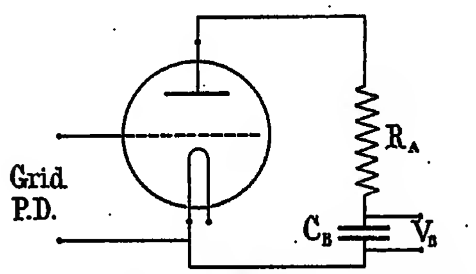

FIG. 1.—Resistance amplifier.

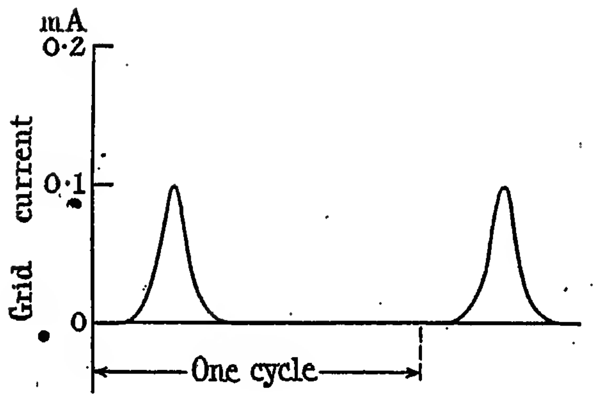

FIG. 2.—Wave-form of grid current with conditions of Fig. 3.

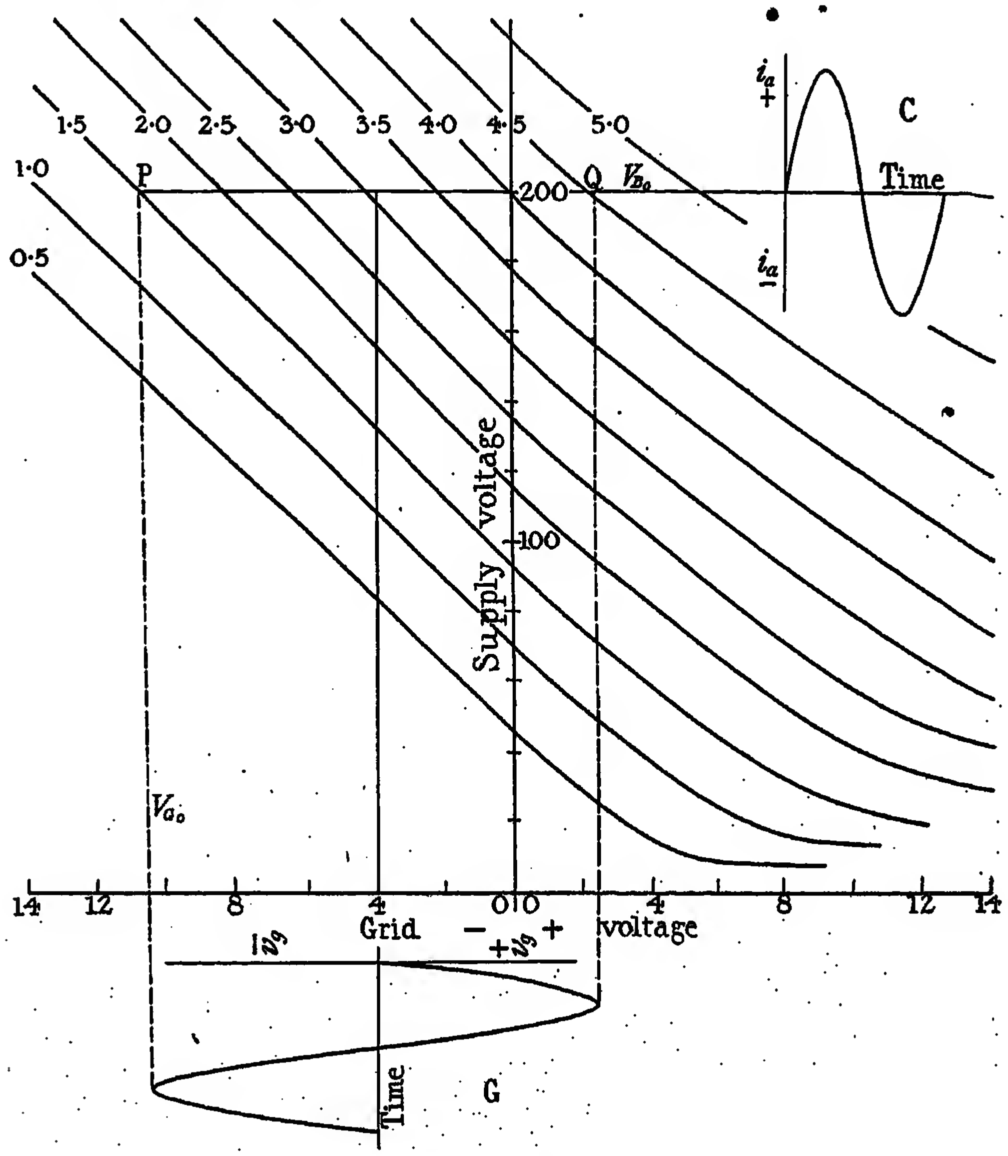

FIG. 3.

plotted out for any given valve, the possible range of anode current and grid voltage over which faithful reproduction can be obtained will be easily seen and the appropriate values of V_{g_0} and V_b can be chosen. The values taken in plotting Fig. 3 are $V_b = 200$, $V_{g_0} = -4$. The amplitude of the fluctuations of V_g is 3·5 volts and of i_a, 1·75 mA.

(*b*) *Transformer amplifier.*—Except in the last stage, a transformer in the anode circuit should closely approximate to a resistance. When very heavily damped, due to its own losses and the load of the valve, and when near the resonant point, this is actually the case. The effective resistance to the alternating P.D.'s the latter is only used to obtain the effective starting-point for any actual battery voltage.

For frequencies other than the resonant frequency of the transformer the conditions are more complicated, and merely plotting the characteristic surface with a correction for a series resistance is insufficient. The surface must be plotted without correction and both the grid and anode fluctuations must be allowed for. The line PQ of Fig. 3 becomes a curve—an ellipse in the case of two pure sine waves—and so long as this curve remains within the zone where the constant-current contours are equally spaced the reproduction will be satisfactory.

(4) Effect of Curvature of the Grid Characteristics.

If the grid voltage fluctuations have any considerable positive values the grid currents will be quite appreciable, and the wave-form of the grid current will differ very widely from that of the grid P.D. Fig. 2 shows approximately the curve of grid current corresponding to the conditions assumed for Fig. 3. The grid currents will generally react on the source of P.D. and lead to heavy distortion. With many amplifiers the peak of the positive half cycle of the grid-filament voltage wave is practically cut off at $V_g = 0$.

The only way of avoiding this difficulty is to render the effect of the grid current negligible. Valves have not yet been produced in which the grid current is negligible when the grid is positive and the anode voltage low, and consequently positive values of the grid voltage must be avoided. This gives another limitation to the range of the anode current characteristic curves that can be used, and indicates that the anode battery voltages should be high, and that the mean grid voltages should be considerably negative.

(5) Effect of the Natural Period of the Intermediate Circuits.

This trouble arises in the case of a transformer amplifier. In the first place any marked resonance means that the effective impedance in the anode circuit is dependent upon the frequency. The impedance—and therefore the amplification—will be greatest at the resonant frequency. Thus any sustained harmonic having this frequency will be unduly pronounced and the speech will appear "tinny" or "drummy," depending upon the pitch of the accentuated harmonic. The larger the number of stages of amplification that are used, the more marked is the effect. In the case of those high-frequency components which are not sustained, the effects are less pronounced. This effect is thus most noticeable with musical sounds and with the vowel sounds.

Secondly, for frequencies other than the resonant frequency, the transformer is no longer equivalent to a resistance, and complications arise from the relative phase of the grid and anode potential fluctuations on account of which it becomes very difficult to determine the wave-form of the anode current when the amplitudes are fairly large.

(6) Reaction Effects.

It is well known that reaction plays an important part in all amplifiers. In the note magnifier the effect is to accentuate the resonance effects mentioned in the previous paragraph.

(7) Distortion in the Last Stage.

The last stage is not unfrequently a source of serious trouble for two reasons :—

(i) The amplitudes are large.
(ii) The "load" on the output transformer—viz. the winding of the loud-speaker—is inductive and this inductance is not constant.

With regard to (i), the output required for a sustained musical note is of the order of 10 mA (R.M.S.) at 5 volts (R.M.S.). To give an equivalent volume of sound with

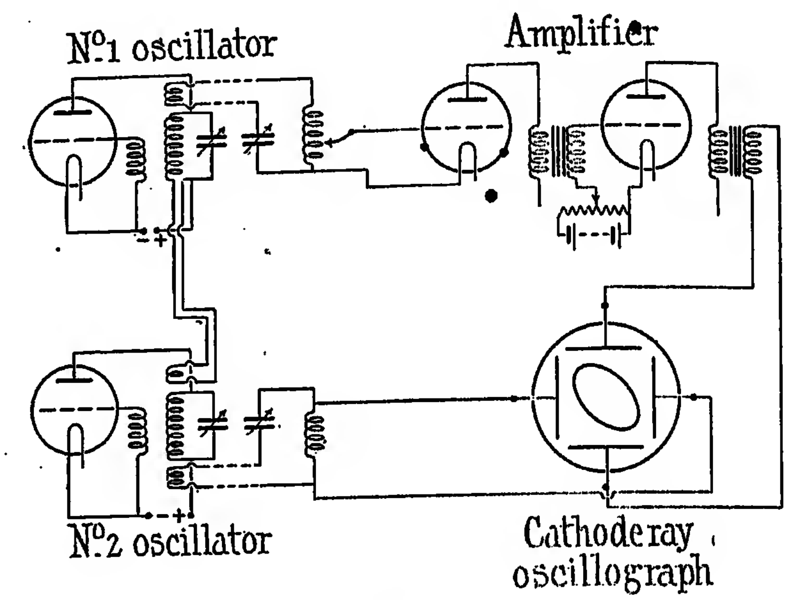

Fig. 4.

ordinary speech a peak value of perhaps double these figures will be necessary, and after allowing for the losses in the transformer it seems that the output from

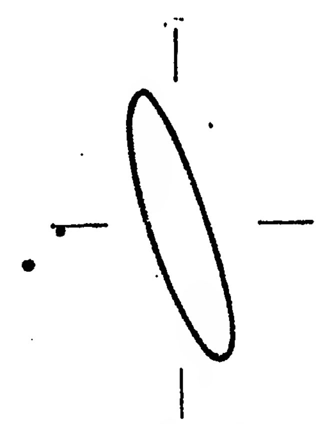

Fig. 5.

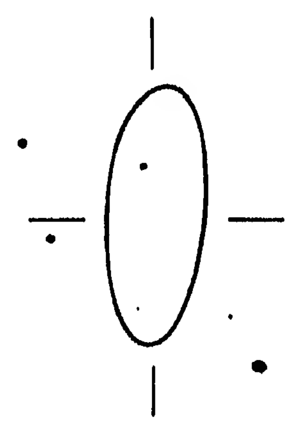

Fig. 6.

the anode circuit of the last valve will be equivalent to an alternating current of peak value 30 mA at an alternating P.D. of peak value 15 volts. A transformer

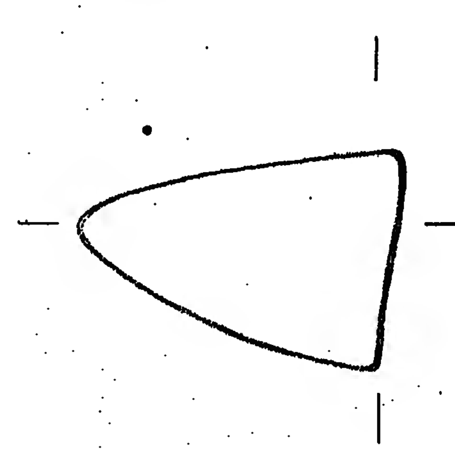

Fig. 7.

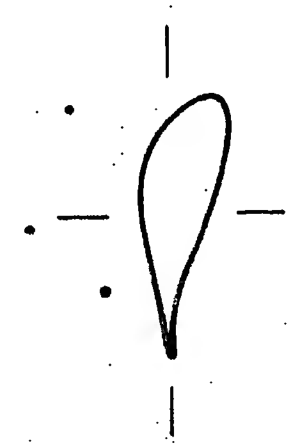

Fig. 8.

is almost invariably used and the actual values would more probably be 10 mA at 45 volts. This involves a valve giving an emission current of perhaps 50 mA

with a fluctuation of anode current over the range 15 to 35 mA; and a voltage at the anode of perhaps 120, fluctuating between the limits of 75 and 165. General numerical considerations such as these show the necessity for valves of considerable output in the last stage.

High battery voltages are also necessary—in the above case the steady fall of P.D. in the anode circuit would be of the order of 50 to 100 volts, and a battery giving something in the neighbourhood of 200 volts would be unavoidable.

With regard to (ii), owing to the inductive nature of the load the last stage cannot be regarded as being even approximately a resistance, and the same effects are noticed as with a transformer operating out of resonance.

(8) Conclusion.

With properly designed valves and circuits it does not appear that any serious distortion can be charged against the amplifier. Valves giving considerable power output must, however, be used in the last stage.

This conclusion has been verified by an oscillographic investigation of a two-stage transformer amplifier. A cathode-ray oscillograph was used, the circuits being given in Fig. 4. In the first instance the output voltages from the oscillators were applied to the deflecting plates of the oscillograph and gave a good ellipse on the screen, thus showing that both were good sine waves. This ellipse is shown in Fig. 5. The amplifier was then brought into use and the output wave when properly adjusted again gave an ellipse as shown in Fig. 6, proving that the sine wave-form was preserved. Unsuitable adjustments or excessive amplitudes showed very marked departures. In Fig. 7 the amplitude was too large and the sharp cut-off in one direction is due to the grid current effectually preventing the grid from becoming appreciably positive. Fig. 8 shows the ellipse closed in at one end owing to bad adjustment giving a mean position near the bottom of the curves of anode current.

THE ACOUSTIC PROBLEMS OF THE GRAMOPHONE.

By H. L. Porter, B.Sc.

In this brief paper it is proposed to give an outline of the work done on gramophone reproduction by P. Rothwell and myself, whilst in the service of the Gramophone Company, Hayes, Middlesex. It is hoped that in this way the problems and difficulties of the subject will be made clear. I am limited by certain restrictions, in that the details of particular methods used cannot be published, neither can the lantern slides exhibited be reproduced. The general method and results which can be given may, however, prove useful in the consideration of the analogous problem of the loud-speaker. The gramophone problem is acoustical and mechanical in nature; in the latter respect it differs from that of the loud-speaker. For the purposes of this discussion I will confine myself almost entirely to the acoustical problem.

The simplest form of commercial recording apparatus consists essentially of a single conical horn in conjunction with a diaphragm. If such an apparatus be set up and its response to a series of simple tones emitted by organ pipes be measured by a suitably mounted mirror attached to the centre of the diaphragm, the characteristic curve shown in Fig. 1 * is obtained, the amplitude of vibration being plotted against frequency of pipe. Preliminary work had been done on the simplification of room acoustics and maintenance of uniformity and purity in the tones. Curve 1 may therefore be accepted as a typical curve under these conditions. The response is very irregular, and it is clear that such an apparatus as we have used would give a very imperfect record. In commercial practice the matter is much worse, for the following reasons:—

(1) The acoustics of the recording room is an unknown and complicated factor.
(2) Many tones are recorded simultaneously.
(3) The tones are complex and are very rarely uniform in intensity.
(4) The characteristic curve is further modified by recording on wax.
(5) In reproduction no needle could possibly pass along the large-amplitude waves in the high peaks, so that further modifications have to be made with further loss.
(6) The reproducing apparatus has its own characteristic response.

The final curve of reproduction from a commercial record must therefore be much worse than shown in curve 1, and in view of this it is surprising that gramophone reproduction is as good as it is. Doubtless the ear is very generous in its behaviour in this respect.

From a study of this curve and many similar ones we decided that the gramophone problem was not, as it had been in the past, a question of improving the "sound box" (as the diaphragm and its housing is termed) independently of the recording horns, or of improving the recording horns independently of the

* The figures referred to in this paper were shown as lantern slides.

sound box, or of both independently of the room conditions. The combination—and here the room must be included—had to be considered as one acoustic system and treated as such. We therefore took a system in its simplest form and sought to arrange its response so that it should be uniform in terms of sound energy over the great range for which the gramophone must cater. This meant approaching the problem in three stages: First, to find to what each large response or peak was due; secondly, to ascertain whether we could control these responses, and, if so, to arrange them to give as much uniformity of response as possible; and thirdly, to reduce the peaks to a suitable value and, if possible, raise the response in the troughs and so smooth out the curve.

Considering these in turn, the "placing" of the peaks led us to an examination of the influence of the diaphragm, its housing, the needle system, the connecting tubes, the recording horn and the room. Each played its part. It was not an entirely easy matter, for the slightest modification in the system often brought about big local changes due to the acoustic proximity of some other factor. However, each peak was successfully "placed," and we found we had gained during the course of the work a good deal of control over the whole system. Next we tried to arrange these peaks in some sort of order, and Fig. 2 shows the result we obtained.

There is a very important point to bear in mind here. If any system is set up in a haphazard manner, i.e. without any acoustical knowledge of the system whatever, one is more likely than not to get two peaks (due, of course, to different factors) falling together or near each other. When this happens a curious placing of peaks occurs and a tremendous massing of response, out of all proportion to the rest of the response, takes place over quite a number of neighbouring tones. In addition it often results in a large reduction of response in regions near at hand. This is shown clearly in Fig. 3.

It was also found that the recording apparatus would react upon the source of sound itself and modify its pitch. Again, it was found difficult to keep the recording apparatus constant in its response for some of our work. The deviations were not such as to affect the general form of the curve, but for later work any changes at all were very serious. Thus temperature had its influence, and many idiosyncrasies of the apparatus had to be investigated before we were satisfied that readings could be repeated from day to day.

Finally we had to eliminate the peaks in the general response curve obtained so far. Mr. Rothwell evolved a very useful plan to reduce these peaks and fortunately, in so doing, found that by the same method he could raise the response in some of the troughs. The final curve for the simple tones is shown in Fig. 4.

The readings from which this curve was drawn are, as in all the curves, amplitudes as ordinates against frequencies as abscissæ. The amplitudes are read on the scale from the deflection of the mirror. Much work was, however, done in tracing out the amplitudes on the waxes, matrices and final records. After certain minor corrections were applied to the system, Fig. 4 can be taken to represent the actual amplitudes obtained on the record. So far, then, we felt satisfied that our corrected system gave us a very good approximation to uniform response over a large range of frequencies. We were not sure, however, whether the balance of response given by Fig. 4 was true for normal hearing; that is to say, we may have allowed for too much in the lower frequencies and too little in the higher, or vice versa. Only a practical trial would settle that. We therefore proceeded to record. We chose the pianoforte as it presented many elements of difficulty and had a great range of frequency, and, moreover, we had made an attachment so that the instrument could be struck one note after another with an even, definite, blow which could be repeated. Here we were confronted with two serious difficulties, one of which we had not anticipated. We expected, of course, that the presence of such a large obstacle as a pianoforte in front of our recording apparatus would make a great difference and we found this to be so. We were troubled, however, to find that the impulsive nature of the pianoforte note was so different in its action from the steady uniform note of the organ pipes, since it made the elimination of the response peaks much more difficult. At last we made a record of the whole series of pianoforte notes where the amplitudes on the records were theoretically of uniform intensity; only a few notes at the top were missing. When we played this record on a gramophone we were confronted with the other half of the problem. We found that the gramophone itself had its own peculiar response, which greatly disturbed the carefully graduated tones on the record. The loud responses and the general distortion depended upon the reproducing instrument used, some instruments being much worse than others.

THE RELATIVE IMPORTANCE OF EACH FREQUENCY REGION IN THE AUDIBLE SPECTRUM—MEASUREMENTS ON LOUD-SPEAKERS

By E. K. SANDEMAN, B.Sc.

THE RELATIVE IMPORTANCE OF EACH FREQUENCY REGION IN THE AUDIBLE SPECTRUM.

The system of ideas bearing on the question of the criteria involved in sound reproduction, which is outlined below, is by no means to be regarded as absolute but is merely an attempt to classify the types of sound characteristic to be preserved and the relative importance of the corresponding physical properties of sound.

The relative importance of each frequency in the audible spectrum depends on what function of hearing is to be served.

There are three essential characteristics of reproduction which naturally occur to anyone considering the matter:

(1) The first is probably intelligibility of speech; it must be possible to exchange ideas with reasonable facility.

(2) The second is naturalness of reproduction of music (and also of speech), which, as we shall see, is a more searching requirement.

(3) The third is the reproduction of speech at correct volume, which is bound up with the first two requirements and involves consideration of the energy of speech.

It is perhaps a surprising result in the case of speech that the importance of a frequency region, from the

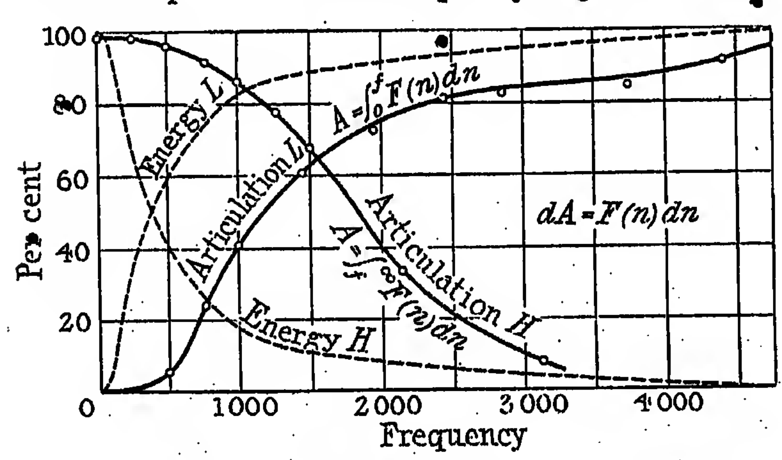

FIG. 1.—Effect upon the syllable articulation and the energy of speech of eliminating certain frequency regions.

point of view of intelligibility, is by no means proportional to its relative importance from energy considerations.

The first requirement of intelligibility is that each isolated syllable shall be correctly interpreted. Syllable articulation may be defined as the percentage of such syllables correctly understood when read from a series of lists of unconnected syllables.

Similarly, word articulation may be defined as the percentage of words correctly understood, while intelligibility is the percentage of ideas correctly interpreted.

Fig. 1 shows the effect upon articulation and the energy of speech of eliminating certain frequency regions.

The full-line curve sloping up to the right shows the effect on articulation of transmitting only those frequencies below the point plotted, and so is of the form

$$A = \int_0^f F(n)dn \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $F(n) \times dn$ is the percentage articulation carried by the frequency region n to $(n + dn)$.

The full-line curve sloping down to the right shows the effect on articulation of transmitting only those frequencies above the point plotted, and so is of the form

$$A = \int_f^\infty F(n)dn \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Differentiating we get

$$\frac{dA}{dn} = F(n) \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

so that the slope of the curve is a measure of the importance of each part of the spectrum in carrying articulation.

If we try to interpret Equation (3) rigidly we are brought face to face with the fact that the slope of the articulation curve for the passing of high frequencies is different from that for the passing of low frequencies. This seems at first to be inexplicable or else due to an error in observation on the part of those who made the tests. The following considerations will, however, make this clear.

By the above treatment we have tacitly assumed that articulation may be expressed as a function of frequency such that the articulation carried by any two regions is the sum of the articulations carried by each individual region. This is actually not the case, since articulation depends on the relative efficiency of reproduction of each frequency region. Hence a discrepancy creeps in if this fact is not allowed for, and practically it is not convenient to do this; actually it will be appreciated from these curves that the error introduced is not serious.

The dotted lines show the energy function in the same way as the articulation. It at once becomes evident that the greatest slope of the articulation curves is not at the same frequency as that of the energy curves; in other words those frequencies that carry greatest energy are not proportionally important from an articulation point of view.

There is as yet no information on the function of frequency portraying naturalness, and it is questionable if such is conceivable or could be of any practical value; we know that perfect naturalness can only be obtained by the uniform transmission of all frequencies within the music or speech range. It is a matter of fact that it is possible to reproduce any one frequency nearly 10 times (energy ratio) better than another before the

ear can detect any departure from naturalness. If we had any measure of æsthetic pleasure, we could obtain a function of considerable value in rating the performance of a loud-speaker by its power to please, simply through an examination of its response characteristic.

The absolute response characteristic of a system may be defined as being a curve plotted between frequency and the efficiency of reproduction at each frequency, this efficiency of reproduction being expressed as the ratio of output to input power. It may thus be greater than unity in the case of an amplifier but is always less than unity in the case of a transmission line.

It is sometimes more convenient to plot the square root of this ratio, which is then spoken of as the voltage or current ratio. In actual practice it is more convenient to plot relative response instead of absolute response as defined above; the shape of the curve obtained is similar, the only difference being the scale.

Referring again to Fig. 1 we see that if we cut off all frequencies below 500 cycles the effect on intelli-

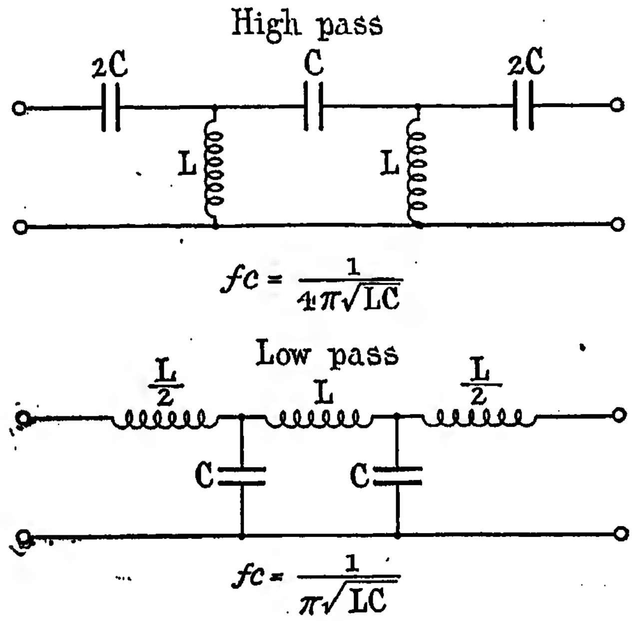

FIG. 2.—Campbell wave filters.

gibility will not be appreciable, although the naturalness with its more rigid requirements is noticeably impaired. If we eliminate all frequencies above about 1 700 cycles we reach very nearly the limit of commercial speech, and any further considerable reduction in cut off produces speech difficult to interpret. The intelligibility is about the same if we cut off all frequencies above 1 500 cycles as it is if we cut off all frequencies below 1 500 cycles.

Fig. 2 shows the type of " high pass " and " low pass " wave filter of the Campbell type suitable for experiments of this kind. The theoretical cut-off frequencies of such filters are given by the following formulæ :—

High pass $\quad f_c = \frac{1}{4\pi\sqrt{(LC)}}$ $\qquad$ Low pass $\quad f_c = \frac{1}{\pi\sqrt{(LC)}}$

MEASUREMENTS ON LOUD-SPEAKERS.

We are now in a position to interpret with some degree of discretion the meaning of the response characteristic of a system, and the next question that arises is how to obtain such a characteristic. The method of obtaining the response characteristic for an amplifier is well known and there is no need to discuss it here.

What we are concerned with is the response characteristic of a loud-speaker operating in its associated circuit; it is necessary to lay stress on this owing to the variation with frequency of the impedance of an ordinary loud-speaker.

Dr. A. E. Kennelly has dealt with the subject of impedance measurements on telephone receivers very thoroughly, and has shown that it is possible to relate the shape of the resonant peaks of the response characteristic to the impedance frequency curve of the loud-speaker. It is, however, a rather laborious process and does not give the complete response characteristic. This method is probably very valuable in analysing the cause of inefficiency and distortion, but as a measure of performance a direct measure of the response characteristic is much more informative.

The most obvious way to do this is by means of a calibrated microphone, that is to say one in which the ratio of output electrical energy to maximum excess pressure due to sound energy is known. It is then

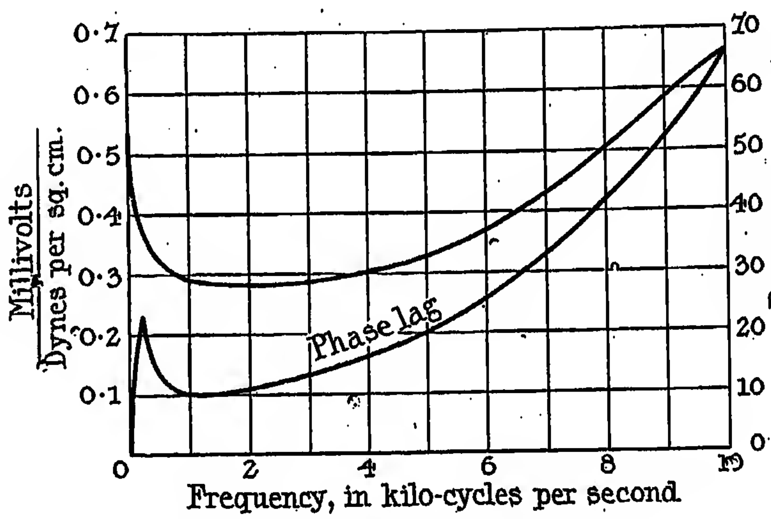

FIG. 3.—Electrostatic transmitter.

only necessary to supply known energy to the loud-speaker and to measure the output sound energy by means of the calibrated microphone in order to obtain a calibration of the loud-speaker. Fig. 3 shows the calibration of a condenser microphone suitable for the purpose. This calibration is accomplished by comparison with a piston-phone and a thermophone.*

Such a calibration would be absolute; that is to say, the actual efficiency of transmission between the input to the loud-speaker and the microphone would be known. This is valuable if we wish to measure the power efficiency of the loud-speaker, but if we are only concerned with frequency distortion then we only require to know the relative efficiency of transmission of each frequency.

In theory this sounds extremely simple, but in practice difficulty is experienced owing to the production of standing waves, resulting in a system of nodes and anti-nodes. The result is that while the microphone may be situated at what is a node for one frequency or

* E. C. WENTE: "The Thermophone," *Physical Review*, 1922, vol. 19, p. 333; also E. C. WENTE: "The Sensitivity and Precision of the Electrostatic Transmitter for Measuring Sound Intensities," *ibid.*, 1922, vol. 19, p. 498.

set of frequencies, it may be also at an anti-node for another frequency or set of frequencies. The result is to produce waves in the response curve; an obvious but rather laborious method of eliminating the effect of these nodes is to take a series of characteristics, moving the position of the microphone slightly each time, and then to draw a mean curve.

It is, however, possible by means of suitable damping material on the walls of the room in which the test is made to reduce the effect of nodes and anti-nodes to a degree where they are practically negligible.

Fig. 4 shows a curve obtained by a combination of these two methods, where the damping was only partial.

The effect of nodes and anti-nodes may be avoided to a large extent by making the test in a large room with the microphone placed very near the horn of the loud-speaker, in which case the volume of emitted

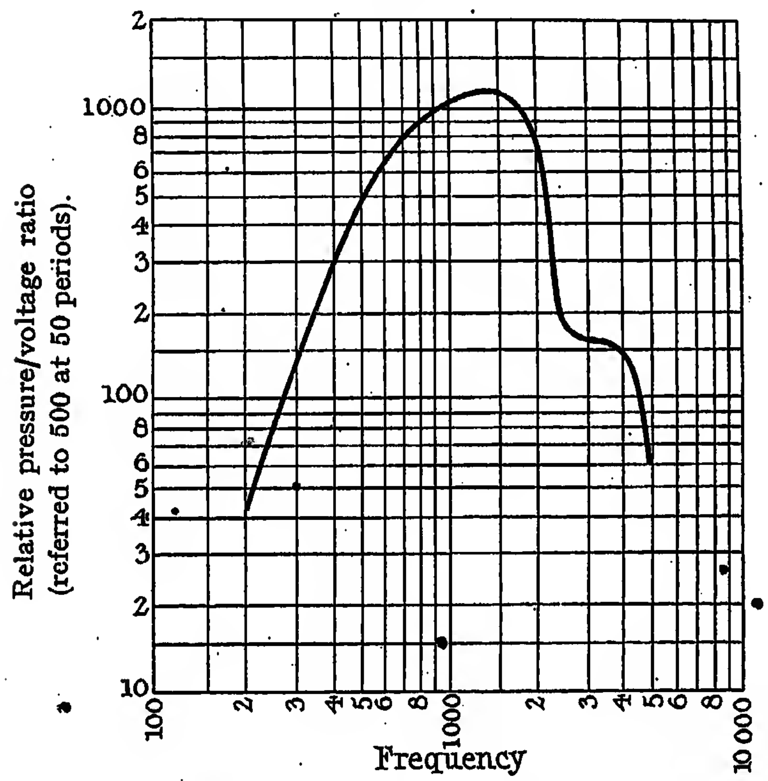

FIG. 4.—Transmission characteristics of loud-speaking telephone receiver.

energy is very much greater than the volume of reflected energy; there is, however, a danger of standing waves being formed between the horn and the microphone.

Another method which has been very successfully used by Mr. L. C. Pocock is to employ a band of frequencies, the frequency applied varying sinusoidally in time between two frequencies at equal distances on each side of the frequency, the response of which is to be measured. Such a method automatically takes an average, eliminating the effect of nodes and anti-nodes and actually tending to prevent their formation.

The formation of nodes and anti-nodes may very easily be demonstrated in a room of ordinary size by connecting a valve oscillator to a loud-speaker. It is found that the intensity of sound varies very considerably from point to point in the room, the nodes being roughly of the order of a wave-length apart, so that the frequency of occurrence of nodes is proportionally greater in the case of high frequencies than in the case of low frequencies. The effects may be best observed if one ear is blocked up, in which case it is possible with quite a loud note, if it is sufficiently pure, sounding in a room, to find a position where a single ear can detect practically no sound. On changing the frequency, an ear in this same position may be found to receive quite a large volume of sound, and the whole system of nodes and anti-nodes will be different.

Returning to the statement that a loud-speaker must be tested in its associated circuit, we can make a modification if we are prepared to make an impedance run on the loud-speaker. In this case we can, if we like, make a test supplying constant current to the loud-speaker at each frequency, and then make a correction for its impedance and that of its associated circuit at each frequency. This is not so direct as testing the loud-speaker in its associated circuit, but it is sometimes more convenient. For instance, if we have a loud-speaker operating in the plate circuit of a valve, we can regard the voltage in the circuit comprising the loud-speaker and the plate circuit as being constant at μ times the a.c. grid voltage, V_g, applied to the valve (assumed to be constant with frequency).

Then the current through the loud-speaker, instead of being constant as was the case under test, is given by

$$\frac{\mu V_g}{Z_P + Z_L}$$

where Z_P is the impedance of the plate circuit, and Z_L the impedance of the loud-speaker at any frequency; and the power input to the loud-speaker is

$$\frac{(\mu V_g)^2}{(Z_P + Z_L)^2} \times Z_L \cos \phi$$

where ϕ is the angle of the impedance instead of $I^2 Z_L \cos \phi$, where I is a constant (i.e. in the case of a test under constant current).

Hence if the ordinates of our response characteristic are expressed in simple power ratios we must make allowance for the variation in impedance of the circuit by dividing each ordinate by the value of $(Z_P + Z_L)^2$ at each frequency and by multiplying each ordinate by some constant (to give a convenient scale), possibly the value of $(Z_P + Z_L)^2$ at some chosen frequency.

If, instead of power ratios, pressure/voltage ratios are plotted, then we must divide each ordinate by the value of $(Z_P + Z_L)$ at each frequency.

We have described this method because it is the one generally used, but it would appear to be much quicker in the commercial case to test the loud-speaker in circuit with its associated amplifier, since all this correction is thereby avoided and all that is required is the response characteristic for the amplifier, which can generally be made sufficiently flat to be negligible.

Fig. 5 shows the circuit arrangements for a test of this nature. M_1 and T_1 show the position of the meter if the test is to include the amplifier A_1, which must then, of course, be calibrated, while M_2 and T_2 show the position for the constant-current test already described.

In actual practice there may be a large number of variations of this method. One that has been very successfully applied is to arrange that the amplification

is such that the net result from the input of amplifier A_1 to the output of amplifier A_2 is a loss at all frequencies. Then it is only necessary at each frequency to insert an amount of standard cable between the oscillator and a headphone to give the same loudness as when the headphone is connected to the output of A_2. It is thus possible to measure the loss in standard miles at each frequency.

Then if P_1 is the input power to amplifier A_1,
P_2 is the output power from amplifier A_2,
$P_2 = P_1 e^{-2 \times 0 \cdot 109\, m}$

where m is the number of miles of standard cable.

The standard cable used in this case is distortionless and has an attenuation per mile equal to the attenuation of standard cable per mile at 800 periods per second. By determining the distortion in the rest of the circuit we can calculate that in the loud-speaker.

It has been attempted in this paper to present the difficulties involved in their most elemental form, rather than to give instances of any very special methods of overcoming them, it being thought that this would be more productive of fresh effort; and it is hoped that the particulars given in the small part of the subject that it has been possible to cover in the time available will be fruitful in this direction.

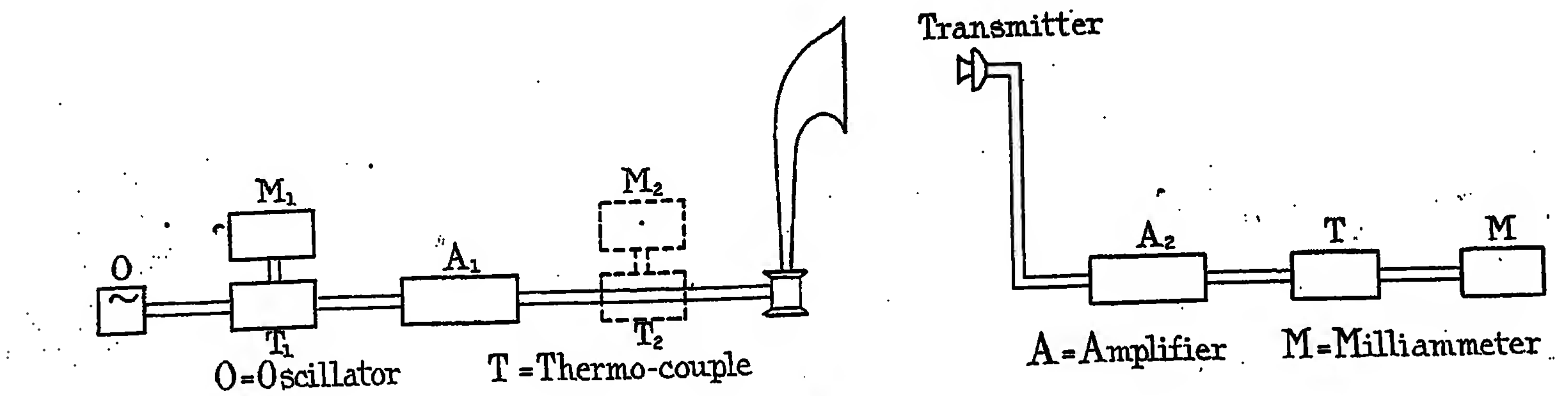

FIG. 5.

THE OVERTONES OF THE DIAPHRAGM OF A TELEPHONE RECEIVER.

By Professor J. T. MacGregor-Morris, Member, and Professor E. Mallett, M.Sc.(Eng.), Member.

It is well known that plates and diaphragms in vibration exhibit resonance at various frequencies, and that at the frequencies of resonance the vibration amplitude under a given impressed force is greater than at others. The frequencies at which resonance occurs, unlike the resonance in the vibration of strings or of columns of air, are not harmonic, i.e. the various overtones are not in the simple proportion of the numbers 1, 2, 3, etc., and the resonance occurs by the plate or diaphragm

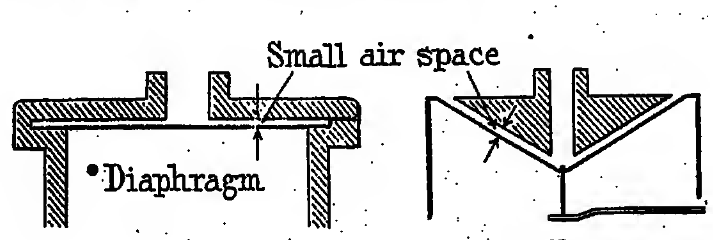

FIG. 1.

TABLE 1.

Experimental Results obtained with a Standard Receiver.

Mode of vibration	Frequency in periods per second	Ratio to fundamental
Fundamental	? 1 050	1
*1 nodal diameter	1 420	2·03
	1 630	2·33
2 diameters	2 250	3·22
1 circle	3 000	4·29
3 diameters	3 400	4·86
*1 circle and 1 diameter	4 000	5·71
	4 550	6·50
*1 circle and 2 diameters	5 760	8·23
	6 150	8·79
2 circles	6 820	9·74
*2 circles and 1 diameter	8 150	11·64
	8 600	12·29

(Those marked thus * were obtained with one of the receiver coils reversed.)

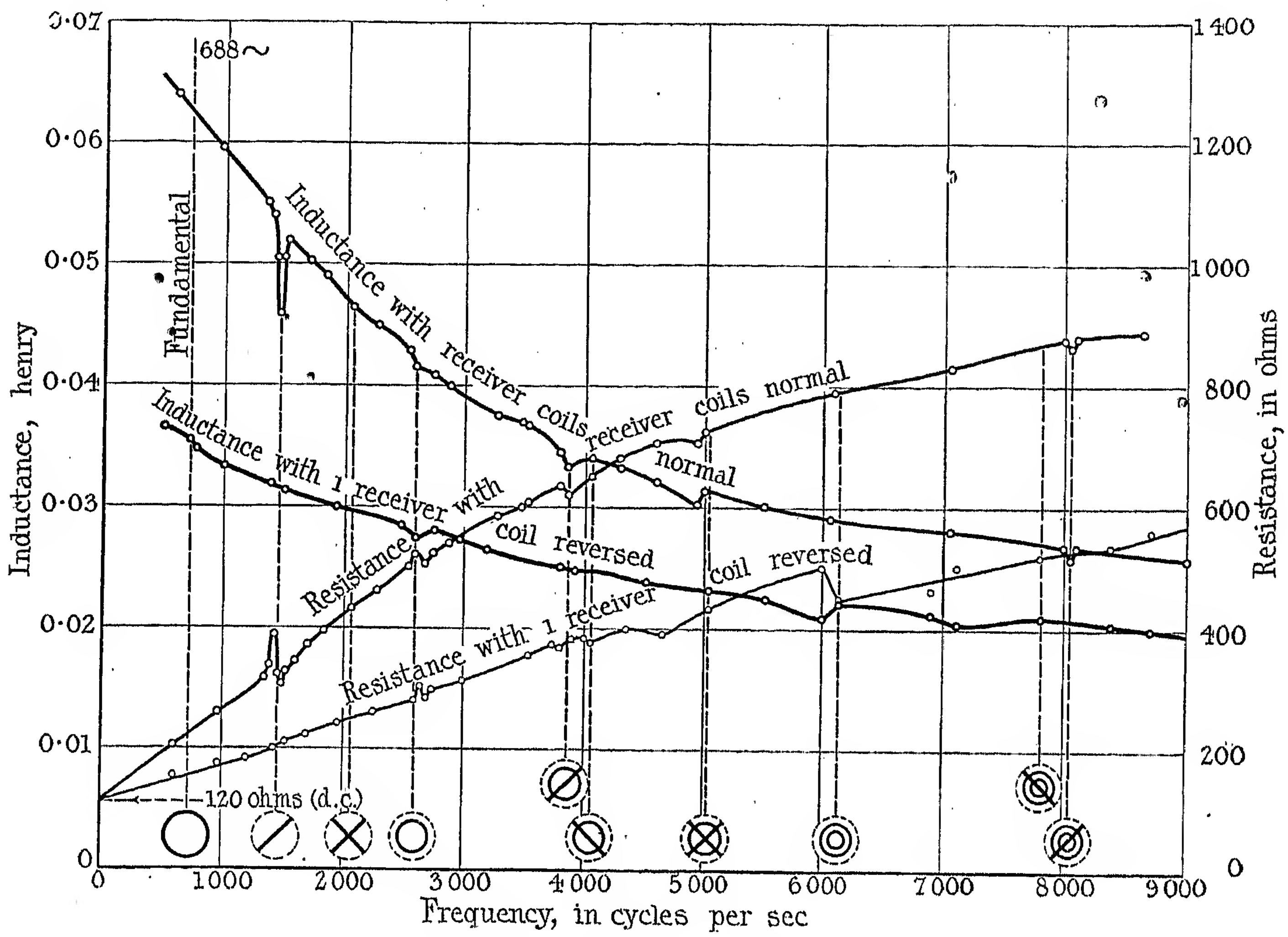

FIG. 2.—Standard Bell-type receiver of 120 ohms resistance tested with a current of 2 mA.

TABLE 2.

Resonant Points on Standard Receiver (120 *ohms*).

Mode	Coil	Note produced		Mode	Coil	Note produced	
		Observed	Plate theory			Observed	Plate theory
Fundamental*	—	f'' to c'''	f''	∅	Normal	$c'''''+$	$c'''''-$
/	Normal	$f'''\sharp+$	$f'''\sharp-$	⊗	Reversed	$f'''''\sharp$	$f'''''+$
×	Reversed	$c''''\sharp$	$d''''+$	◎	Normal	$g'''''\sharp+$	$f'''''\sharp+$
○	Normal	$f''''\sharp$	$f''''-$	∅	Reversed	$c''''''-$	$c''''''-$
✳	Normal	$g''''\sharp+$	a''''				

NOTE.—The plus sign means that the note is sharp but by less than half a semitone, and the minus sign that the note is flat by less than half a semitone.

* Further experiments have shown that the fundamental observed, marked c''' above, is in error owing to masking from a wide band of resonance due to the cap and casing of the receiver, and the actual fundamental is at 686 for the diaphragm. The following values were obtained :—

By inductance bridge without sand : 688·5
" " " " : 684
By inductance bridge with sand : 668

vibrating in portions and not as a whole. These various modes of vibration can be exhibited by the well-known method of Chladni, simply by sprinkling sand on a diaphragm. We are much indebted to Mr. Dutton of the City and Guilds (Engineering) College for assistance in this matter.

The point arises as to what bearing, if any, this has on loud-speakers. Many loud-speakers use a diaphragm or vibrating plate of some kind or other. In some the plate is directly actuated by the electromagnets as in the ordinary telephone receiver, while in others it is moved by a reed or a moving coil. But whatever the means employed to impart the motion, the facts are the same, that a diaphragm of some form or other is maintained in vibration by an impressed force and so a sound wave is produced.

It seems natural to conclude, therefore, that all loud-speakers of these types must have resonant frequencies which are to be ascribed to the various modes of vibration of the diaphragm. The question as to how sharp these resonances are, depends on the damping. In the case of the ordinary receiver, considerable damping is introduced by the closeness of the ear cap to the diaphragm, and still further damping is introduced when the receiver is placed to the ear. In at least two different types of relatively successful loud-speakers (A and B) a similar device is adopted to introduce damping.

It would therefore seem to be a question of a judicious balancing of the damping against the resonance. Without the resonance, i.e. with very strong damping, the response would be very poor, but uniformity over the frequency range would be assured. With resonance the response is great, but there is lack of uniformity.

That the frequencies at which resonance occurs with an ordinary diaphragm are within the necessary range in music seems to be certain, as Table 1 * would indicate, and as will have been heard during the demonstration.

There are four methods of obtaining the resonant frequencies of a telephone receiver diaphragm :—

(a) By intensity of sound produced.
(b) By Chladni's sand figures.
(c) By Western Electric cathode-ray tube indicating sudden change of power factor.
(d) By inductance bridge measurements.

In all cases an alternating current is supplied by a valve oscillator and the frequency is gradually increased, when the various overtones become apparent at their respective frequencies.

In the inductance bridge method the passage through a particular mode of vibration is rendered evident by a sudden drop in the inductance and a return to the smooth curve, and a sympathetic change in the effective resistance curve. These changes have been examined very thoroughly by Dr. Kennelly for the fundamental mode of vibration.

In the accompanying curves (see Fig. 2), determined by Mr. M. Stern at East London College, these changes are shown for a number of the overtones as well, and the sand figures belonging to the respective modes are also shown on the graph. Two pairs of curves are given, one with the two coils in the receiver connected in the usual way and the other pair with the two coils in opposition. It will be seen that owing to lack of complete symmetry in construction of the receiver, certain modes are evident in both pairs of curves.

The above results are given in the pitches of the various overtones in Table 2, and it will be seen that the plate theory is in close agreement with the observed values; only in one case is there a difference of more than a semitone.

* Extracted from a paper published in the *I.E.E. Journal*, 1923, vol. 61 p. 1314.

AUDITORIUM ACOUSTICS AND THE LOUD-SPEAKER.

By G. A. SUTHERLAND, M.A.

The conditions of good hearing in an auditorium are: first, uniform and adequate loudness; secondly, distinctness, which means freedom from undue overlapping of successive sounds; and, thirdly, freedom from distortion, i.e. the preservation of the proper relative intensities in the simultaneous components of a complex sound. A pre-requisite to the attainment of such qualities is the ability to express them in definite form, and also to express with definiteness the way in which the shape and the lining and furnishing of a room contribute to produce these effects.

Uniform loudness is associated in practice with the absence of curved walls, which produce main and subsidiary foci, and, unless suitably covered, always constitute a menace to good acoustics. With flat walls the distribution becomes sensibly uniform within a small interval of time, and, when a source commences to emit sound, the energy density has been shown by Jäger,* making assumptions as to conditions that are sufficiently close approximations to those actually occurring, to grow according to the equation

$$E = \frac{4A}{avS}\left(1 - e^{-\frac{avS}{4V}t}\right)$$

where E is the average energy density at time t, A is the energy emitted per second, V is the volume of the

* S. JÄGER: *Sitzungsberichten der Kaiserl. Akad. der Wissenschaften in Wien*, 1911, vol 120.

room, v is the velocity of sound, and e is the exponential. S is the total surface presented by walls, ceiling, floor, furnishings, etc., and a its average absorption coefficient. If there are surfaces S_1, S_2, S_3, S_4, etc., with coefficients a_1, a_2, a_3, a_4, respectively, then clearly

$$aS = a_1S_1 + a_2S_2 + a_3S_3 + a_4S_4 + \ldots$$

Similarly, when the source is stopped the time of decay is given by

$$E = \frac{4A}{avS} e^{-\frac{avS}{4V}t}$$

The value of the maximum intensity attained, $E_{max.}$, which is $4A/(avS)$, varies directly with the rate of emission of energy by the source, and inversely as the total absorbing power of the room.

If a room be very large, S is necessarily large and the maximum intensity can be changed only by varying A or a. Thus it will be impossible to fashion too large a room satisfactorily for sounds of limited strength (i.e. where A is small), since to make $E_{max.}$ large a

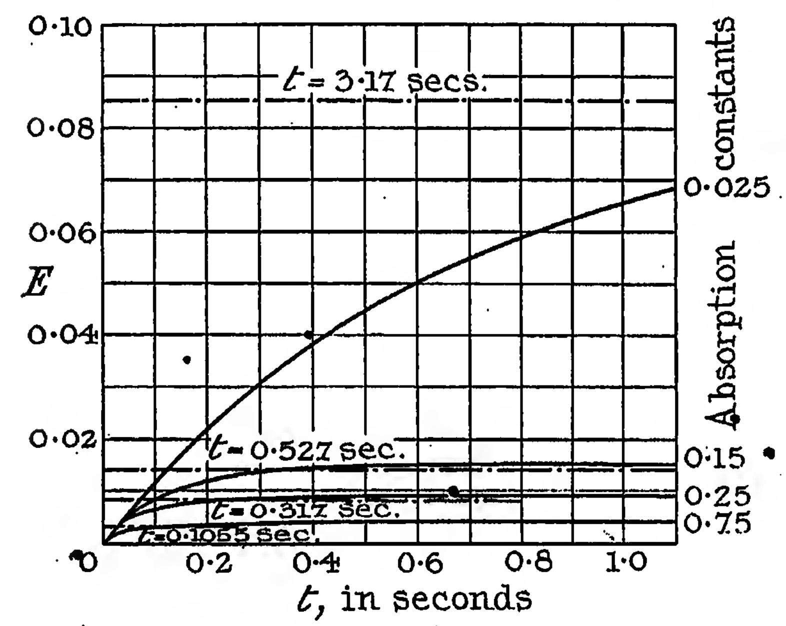

FIG. 1.—Growth of sound intensity in a room for various degrees of absorption of its boundaries. The time-values associated with the horizontal dot-and-dash lines give the time in which the intensity grows to 99 per cent of the saturation value.

would then have to be made small, the effect of which is, as will be seen, to increase the rates of growth and decay and so militate against distinctness. The term "adequate loudness" has no meaning except when considered in relation to distinctness. The rates of growth and decay also depend on the value of S/V, which is smaller the larger the room. Thus two rooms having the same proportions and lined with the same material will have different acoustic properties unless they are identical in size.

The meanings of these expressions for growth and decay can perhaps best be appreciated by reference to the following curves, most of which are due to Eckhardt.* The first series (Fig. 1) shows how the rate of growth in a room of volume 1 000 cubic metres changes with the average absorption coefficient of its walls, the conditions varying from an empty room with bare hard walls to a room with a full audience and a large amount of absorbent lining material. It will be seen that the maximum intensity attained is greatest for the empty room, but that the time to attain this maximum is also greatest. If the decay curves, which are the same curves inverted, are plotted, then the time of decay is clearly seen to be greatest for this case also.

The effect of varying the volume of the room is shown by the next series (Fig. 2). The intensity is seen to rise most slowly in the case of the largest room and also to attain the smallest maximum.

In speech, where the emission is discontinuous, the effects may best be demonstrated by drawing a separate curve for every syllable and summing these to show the variation in total intensity. The result is shown in Fig. 3. The dotted curve represents the resultant. In the case selected it will be noted that at any

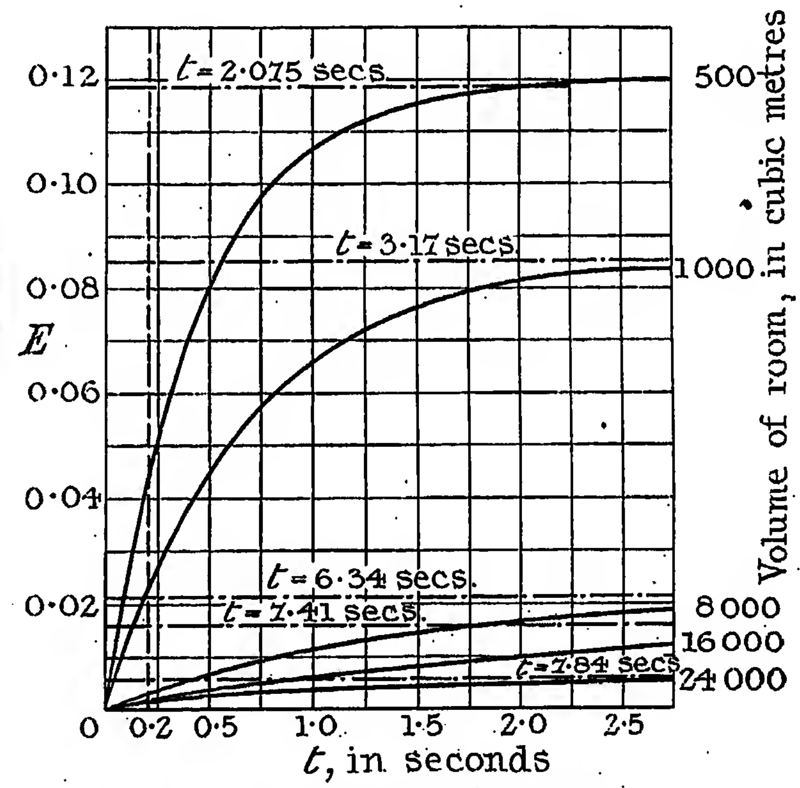

FIG. 2.—Growth of sound intensity in rooms of different volumes, the boundaries being of the same poorly absorbing material in all cases.

instant about 60 per cent of the sound heard is due to previous syllables and only 40 per cent to the syllable actually being uttered, also that the variation in intensity due to the discontinuous articulation is only a small percentage of the total intensity, conditions which inevitably mean indistinctness.

The effect of speaking at half the rate in the same room is shown in Fig. 4. The maximum intensity is only about half what it was, but the syllable actually being uttered contributes 60 per cent of this. This represents an improvement, the variation between syllables being 40 per cent of the maximum. It is to be noted here that although the discourse seems disjointed to the speaker it will not seem so to the audience.

If we take a room of the same size but of higher absorbing power the maximum attained may be reduced to one-tenth of the previous value, as indicated in

* E. A. ECKHARDT: *Journal of the Franklin Institute*, 1923, vol. 195, p. 799.

Fig. 5, but each syllable contributes 94 per cent of the sound heard at any instant, and the variation between syllables is about 45 per cent of the maximum. This represents a state of affairs in which hearing is satisfactory, and it will thus be seen that, for speech, distinctness is more important than loudness.

It is possible to carry the process further, and in this case we get the effect shown in Fig. 6. The resultant

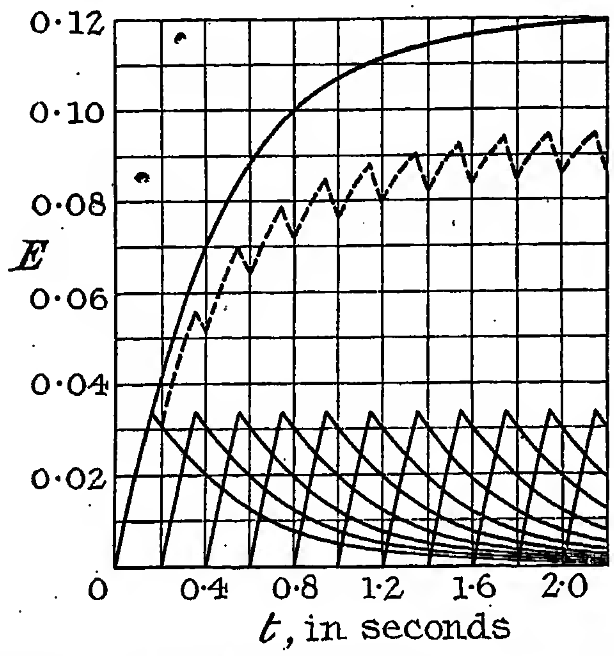

FIG. 3.—Growth and decay of sound intensity for syllable emission in a room of too small absorbing power.

curve differs so little from the components that it has not been drawn. Here the peak intensity is about one-third that of the previous case, but the drop between syllables is about 90 per cent of this. By common agreement such a state of affairs is assumed to be inferior to the previous state, partly, perhaps, because of the small peak intensity, partly, too, because we are

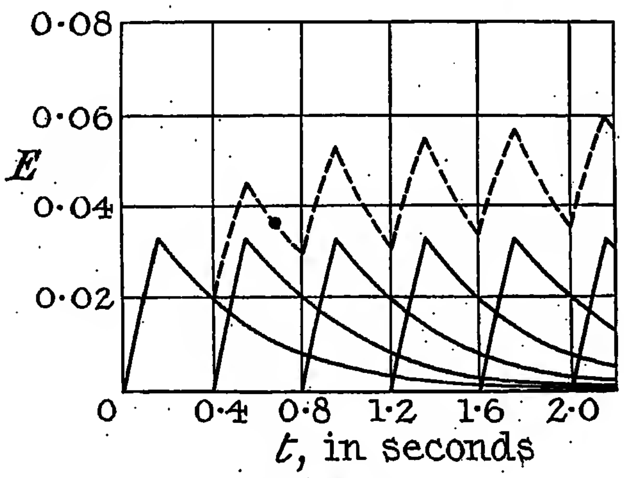

FIG. 4.

so accustomed to a certain amount of overlapping that a condition in which it is absent seems unnatural, but undoubtedly also because ideally a speaker's utterance should have in it something of the character of music, and everyone would unite in condemning as "dead" a passage of music in which there was no blending of successive sounds.

To the slow decay of sound in a room indicated by the foregoing series of curves the name "reverberation" has been given, and exhaustive experiments by Sabine * have shown that the best condition as regards distinctness is associated very approximately with a particular reverberation period which in a room of a given volume has one value for speech, another for chamber music, and a third for orchestral music. A logarithmic curve like these is completely determined if we can measure the time of decay to $1/e$ of the initial value.

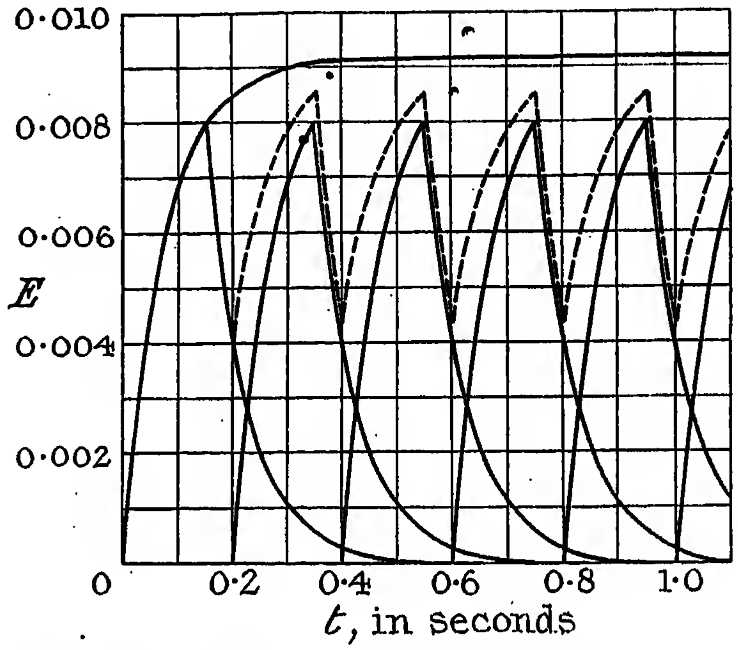

FIG. 5.—Growth and decay of sound intensity of syllable emission in a room of proper absorbing power.

In any ordinary room this time is too short to be capable of accurate measurement, and Sabine measured instead the time of decay to inaudibility of a sound initially 10^6 times the minimum audible intensity. This he calls the "period of reverberation." By doing this in rooms lined with different materials he was able to assign absorption coefficients to linings commonly used. This enables calculation to be made in advance of construction

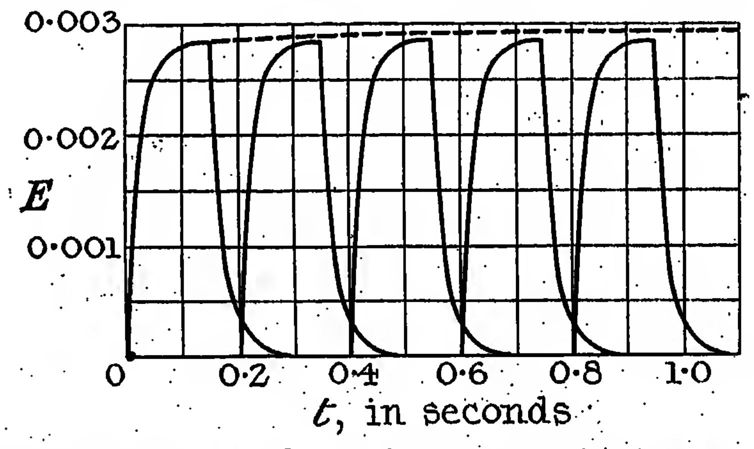

FIG. 6.—Growth and decay of sound intensity for syllable emission in a room of too great absorbing power.

and the desirable reverberation period to be assured from the start. Sound, being a form of energy, cannot be got rid of by the scattering produced by irregularities in the walls, etc. It remains audible until converted either directly by air friction into heat, or into some other form which will eventually become heat. Thus the most effective absorbents of sound are porous linings and furnishings, the relative merits of different linings

* W. C. SABINE: "Collected Papers on Acoustics," 1922.

being indicated by the curves in Fig. 7. Curve 1 is for a painted brick wall; curve 2 is for plaster on tile with a finishing coat; curve 3 is for wood panelling; curve 4 is for a special tile called Akoustolith; curve 5 is for a special hair felt; curve 6 is for hair cushions; curve 7 is for cotton wool cushions, and curve 8 for an audience as ordinarily seated. It will be seen that an audience is the best absorber of sound.

Where speech is concerned the difficulty usually is to introduce sufficient absorbent material, a difficulty which, as we have seen, increases more than propor-

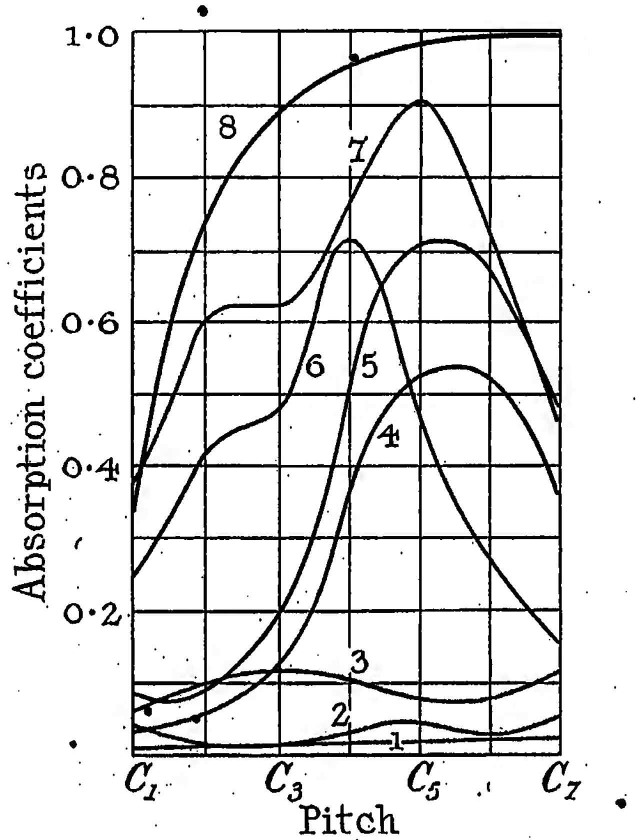

FIG. 7.—Showing the absorbing powers of different materials.

tionately with the size of the room, since the times of growth and decay depend on S/V, and V increases more rapidly than S. When we come to consider the possible function of the loud-speaker we see that much more satisfactory hearing is likely to be attained by distributing an audience into a number of small rooms with a loud-speaker in each, than by attempting to accommodate all in a large hall. Even if the large hall be full the audience is not so effective in reducing reverberation as in smaller rooms. If the room is partly empty the situation is considerably worse.

For music, where a longer reverberation is desirable, the opposite arrangement may give the better results. It is impossible to generalize, however; each case would have to be settled on its merits.

One thing that stands out quite clearly is that nothing is to be gained by having a loud-speaker with a rate of emission of energy many times that of the human voice. Almost all halls suffer from excessive reverberation and the louder the initial sound the greater is the confusion produced, since the louder sound lasts longer and there is more overlapping. This is a matter of common experience; in fact a sure indication that a room is suffering from excessive reverberation is furnished if increasing the loudness is found to increase the defect.

A point to which we have not yet directed our attention, and which can be touched on only briefly, is the question of accurate rendering or freedom from distortion. It is customary for physicists to regard the quality of a note as being completely determined by the relative intensities of the different vibrations leaving the source. Clearly the sound heard depends on the relative intensities of the vibrations reaching the audience. The different wave-lengths, as Fig. 7 shows, are far from being absorbed equally. Sabine quotes a case where with an 8 ft. organ pipe the introduction of felt into an empty room reduced the ratio of the first overtone to the fundamental by 40 per cent, that of the third overtone by 50 per cent, and the fourth by 60 per cent. With a 6 in. pipe, on the other hand, the effect was to accentuate the overtones, whereas all notes below the 6 in. fundamental were purified. The effect of an audience was still different, viz. to purify all notes up to C4, 512, and to have very little effect on tones above this. For C1, 64, the first overtone was decreased 65 per cent relative to the fundamental, and the second was decreased 75 per cent.

Generally we may say that if the sound from a loud-speaker tends to be too rich in higher-pitched notes, then the presence of a large audience is likely to have a corrective effect. As before, it will be advantageous to use several smaller rooms rather than one large one. The case of music is too complicated for treatment here. So far as the author is aware, the judgment of musical authorities has never been expressed in such a form as would make it applicable. No doubt the relative numbers of the different instruments in an orchestra have been fixed empirically, having regard to the conditions normally prevailing in concert halls.

SOME DIRECTIONS OF IMPROVEMENT IN THE LOUD-SPEAKING TELEPHONE.

By S. G. BROWN, F.R.S., Member.

It is difficult to discuss the problem of the loud-speaker in the short time available, and accordingly my remarks must be confined to one or two general aspects which occur to me.

It may be remarked that, for the want of the perfect transmission system, it is not possible to determine the real inefficiency of the present-day loud-speaker. We presume that it is inefficient because in the electrical transmission to it we have never approached the perfection of listening direct to, say, the music of the orchestra itself.

The loud-speaker consists, among other things, of a diaphragm which operates in an enclosed chamber in the manner of the piston of a pump. A hole is provided

in the cover of this chamber, and air is forced in and out through it as the diaphragm vibrates. The smaller the hole, within reason, the greater will be the velocity of the air as it leaves the chamber, and, as the sound energy is proportional to the square of the amplitude, the output of the loud-speaker can be materially raised by a suitable size of hole.

Connected with this hole is a tapering funnel or trumpet. The object of this is to transmit the sound energy to the outer space with as little loss as possible. The air in the funnel vibrates as in a double open-ended tube. The natural period of the air enclosed in the trumpet is similar to that in an unstopped organ pipe.

This natural vibration of the air column is superimposed upon the vibrations set up in the air by the diaphragm. It can, however, be removed by drilling suitable holes in the tube along its axial length. The first hole would be mid-way along the trumpet in order to eliminate the natural frequency of the column. The next overtones are removed by drilling holes respectively one-quarter and one-eighth of the way along the axial length, their diameter being made smaller as the diameter of the trumpet diminishes. The improvement brought about by this device is recognizable by a trained ear.

As regards the material of the funnel, a rigid wall is desirable for the proper enclosure of the vibrating air column, and to this end it should be of heavy metal and of thick cross-section. If the trumpet walls are too thin the force of the air expanding as sound will distort or swell them, causing them to resonate. (We are speaking, of course, of ideal conditions, and manufacturers, from considerations of weight, etc., must use lighter material.)

The vibrations of the diaphragm are not all imparted to the air, but escape into the metal enclosure and thence up the metal of the trumpet. It is therefore a good plan to insulate the sound-producing element from the trumpet and casing. One manufacturer fits his funnel on by means of a rubber sleeve; this appears to be a good arrangement.

Even the best of modern loud-speakers causes a certain amount of distortion which I attribute to the free vibrations of the diaphragm. If we could obtain the necessary air waves with less amplitude of movement at the source, greater freedom from distortion would result. Possibly this might be done by employing a larger diaphragm, suitably stiffened without sacrifice of lightness.

Alternatively, we can produce sound vibrations by other kinds of pressure devices, such as the "Frenophone." This instrument consists of a rotating glass disc and a steel-backed cork pad resting in contact with its surface. The cork is linked to a loud-speaker movement. A telephone receiver presses on the back of the cork by means of an elastic steel pin. Telephone currents, therefore, by operating the receiver, alter the pressure of the cork on the glass disc, thereby varying the frictional drag and working the loud-speaker. It is believed that this combination gives greater clearness in the sound emitted, and the Frenophone may be regarded as a step onwards in the direction of the perfected loud-speaker.

THE CHARACTERISTICS OF A NEW TYPE OF LOUD-SPEAKER.

By Captain P. P. Eckersley.

There seems to me to be no doubt that the weakest link in broadcasting at the present moment is the receiver, and that the weakest link in the receiver is the loud-speaker. The British Broadcasting Company is certainly transmitting on an arbitrary basis, but a basis on which remarkably good results can be obtained if the loud-speakers are properly designed. The problem of loud-speakers is balanced between two ideas: Is the aim to be efficiency, i.e. are sounds to be intelligible, or is the transmission to be perfect from the point of view of music? There appear to be two absolutely distinct types of instrument: the efficient resonant loud-speaker which will fill rooms of large size, and the loud-speaker which will be just sufficient for an ordinary drawing-room. In the former type I think that much must undoubtedly be sacrificed. It has, however, been pointed out by one speaker how difficult it is to get efficiency and at the same time perfect quality. I propose to demonstrate a loud-speaker of the drawing-room variety which gives very good quality. I feel that it has some qualities that no other loud-speaker has, in that there is a certain warmth in the bass. Many loud-speakers are very resonant at about 1 000 p.p.s. This loud-speaker seems to be resonant somewhat lower in the scale, and I think that this is good from the point of view of music. A really efficient and perfect-quality loud-speaker, although it would probably be most expensive and consume a very great amount of power, would be a great achievement. If this meeting helps to bring about that achievement I shall feel that it has not been called in vain. An efficient instrument is possible theoretically, and I think that it will come in time.

[Captain Eckersley then demonstrated on the Gaumont-Lumière loud-speaker.]

Discussion at the Joint Meeting of The Institution and the Physical Society of London, 29 November, 1923.

Dr. W. H. Eccles: The loud-speaker of to-day is really an immense achievement and does in an almost perfect manner what could not have been done 20 or 30 years ago. By its aid the science and practice of communication is being revolutionized. It is now possible for a single voice to speak to millions of people; in every country in the globe it must now be realized that the orator, the politician or the preacher, can address audiences of a size that was undreamt of a few years ago. This is being done in two ways. In this country we have the loud-speaker combined with wireless broadcasting to carry the speaker's voice to hundreds of thousands of people; but in America the loud-speaker has also been largely developed in what is called the "public address" system. In that case a speaker may be in a great auditorium or hall, or possibly in the open country; he speaks in ordinary tones to a microphone, and the speech currents are passed through amplifiers to a large loud-speaker or a series of loud-speakers. By that means an audience of 700 000 people gathered on the spot has been enabled to hear the speech. This is bound in due course to produce in every country a profound change in our political and social conditions; the voice carries personality so very much better than the printed word. It seems to me that the loud-speaker will become the great rival of the printing press, which is not an unadulterated blessing, especially in these days when large organizations of capital can to a large extent dictate public opinion by means of innumerable journals. Let us by all means have something to compete with that, even though it may be equally liable to fall into bad hands. I thought it would be appropriate for me in opening the discussion on the technical side to point out the enormous task that the loud-speaker has to attack. Its construction is faced with such exigent demands, that one would say in advance that it would not be possible to make an instrument to meet the requirements. For instance, the periodicity of speech waves varies from 100 to 6 000 per second. No engineer attempts to make an alternator to operate over such a range of frequency. In music the frequency-range is greater; it may be from 40 to 10 000 periods per second, but in fact the ear is sensitive, in middle life at any rate, from 40 to 20 000 vibrations per second. A loud-speaker designed to give a natural effect must be capable of some such range as that. In addition, the loud-speaker which is to satisfy the ear must have an enormous range in the energy of the air pressures. The air pressures in ordinary speech have been measured, and they range from the one-thousandth part of a dyne per square centimetre to 100 dynes per square centimetre. In other words, a loud-speaker to give a natural effect must be capable of producing a range of pressures about a millionfold. Again, the minuteness of the energy stream is very surprising; in a quiet room every word can be heard at several yards' distance if the speaker pours into the ear of the listener a volume of sound equivalent to about 10^{-8} watt. With an orchestra it is estimated that the ratio of power required between *fortissimo* and *pianissimo* is 50 000 to 1. Speech is quite intelligible if the sound is 100 times that which leaves an ordinary speaker's mouth, or even if it is one-millionth of that power, i.e. a ratio of 10^8 to 1. This can be emphasized in the following manner: Suppose that a loud-speaker on a building emits sounds of an energy of 1 kW. At three miles, speech would be easily intelligible by the unassisted ear, supposing the ear to have an effective area of about 1 cm^2 for receiving direct-energy air waves. If an ear trumpet were used which would collect the energy falling on 1 m^2, then speech would be intelligible at a distance of 200 to 300 miles. That shows how very sensitive the ear is and how much it expects. If we find that the human voice, the larynx and other organs, can make these variations of great range of power and frequency, we ought to be sufficiently encouraged to say that mechanism will, no doubt, in time be evolved to do the same. It has, in fact, been evolved. Or we ought to say that if the mechanism of the middle ear can work, it should surely be possible to make a machine that will perform similar feats, seeing that the problem is a physical one and not a physiological or psychological one. That task has been largely accomplished in the past few years. The Western Electric Company's laboratory in New York has probably done more than any other laboratory in the world to accomplish this task, and I think that it will be useful to make some reference to the work that has been carried out there. Their public address system takes speech energy into a microphone, and the currents in that microphone represent an energy of about 10^{-8} watt. After being amplified they finally reach the loud-speaker. The loud-speaker responds excellently between 200 and 1 600 periods per second, and the electrical energy put into it is 40 watts. This represents a ratio of magnification of 4×10^9 to 1. The result is so good that the voice coming from the loud-speakers in an open space, if the listener is the correct distance away, is indistinguishable from the voice of the person speaking. Now we have to compare what has been accomplished with what has been said in the various papers read during the meeting. It seems that there are three points to be considered in improving loud-speakers. The first is that we require to amplify all frequencies equally, or substantially equally, even over a wide range. In addition, the instrument must work in such a manner as to give the energy to the air equably. The second is that it must not introduce asymmetrical distortion. Helmholtz in his "Sensations of Tone," in discussing the human ear points out that it is a diaphragm which is heavily loaded on one side with the bones in the inner ear. He sets down two differential equations, and deduces the rather surprising fact that the asymmetry

introduces harmonics and combination-tones. If one has those in a loud-speaker, i.e. if one has a diaphragm which is acted upon very unsymmetrically and responds to equal currents in opposite directions with unequal movements, then these combination tones will be obtained. That is what I call the second difficulty in the design of loud-speakers. The third difficulty is that impulsive sounds produce damped trains of oscillations of the diaphragm. If those are not rapidly damped out they provide another source of trouble. In conclusion, I should like to say that it is surprising to think that the efficiency of a loud-speaker reckoned in the ordinary way, i.e. the ratio of the electrical power which is put in, to the mechanical power which is got out, is only about 0·1 per cent. If that is so, it seems to me that the improvement of the efficiency of the loud-speaker is the next task confronting the investigator and designer.

Adjourned Discussion at the Joint Meeting of The Institution and the Physical Society of London, 14 February, 1924.

Sir Richard Paget: I entirely agree with Mr. Sutherland that audibility is a matter of precision of aural resonance rather than of amplitude. For example, whispered sounds can be heard, as I have experienced, over long distances and by large audiences, provided they are whispered properly so that the resonances are clear. Many of the human speech sounds, especially the consonants, are really essential transients. They depend not upon any one group of resonances, but upon how those resonances are changing. In other words, we recognize the shape of the frequency-time curve for that particular sound. Take, for example, the consonant sounds in "t," "p" and "kee." Those sounds differ only in the shape of the curve of approach of the resonances to the ultimate resonances of the vowel sound "ee." Similarly, the consonant in "la" is essentially a transient, and if we extend the time curve of the resonances of that sound we get what is practically a diphthong. The "l" sound is entirely lost to our ears and it becomes merely a succession of vowel sounds. From that it would follow that the ideal reproducer must be sensitive to frequency changes and, as Mr. Pocock points out, it must be free from any resonances which would cause this or that component to linger beyond its allotted span. On the question of "imitation" which Professor Rankine raises, it seems to me important that what is given in that imitation shall be true. The same applies to painting; it does not matter how much an artist leaves out as long as he does not put anything in which is wrong. Further, the scale of magnitudes may be fundamentally altered without the faithfulness being apparently affected. A constant component, e.g. the scratching of a gramophone needle, is permissible, provided it is not too loud. Ultimately the ear becomes accustomed and ignores that. An interesting example was given of the ability of the ear to take certain components for granted, in Dr. Eccles's experiments for producing artificial vowels in a telephone by means of electrical resonance. Dr. Eccles produced quite recognizable successions of vowel sounds by using only the upper components of my vowel chart, and the human ear filled in the lower resonance, provided that the upper resonances were not ambiguous. As to horns, the vice of these seems to me to lie, not in the fact that the horn possesses resonances of its own, but that it gives them an exaggerated importance when they come along in the ordinary course of speech. Mr. Sandeman's Fig. 1 refers, as I understand it, to syllabic articulation as a whole. If that chart had been limited to the syllabic consonants, such as "s," "z"; "th," "dh"; "f," "v"; "p," "b"; "k" and "g," his curves would have indicated that a much greater importance is to be attached to frequencies of between 2 000 and 3 000 as the lower limit, and 6 000 or 7 000 as the upper limit. For instance, in my own voice "s" has a principal resonance of over 6 000; "sh" has a principal resonance of over 3 000; "f" has a component of between 5 000 and 6 000; while "th" has a component of between 2 500 and 3 400, varying with the vowel with which it is associated. Similarly, "k" has an initial resonance of something like 3 000, and "t" has a resonance of between 3 000 and 6 000. On the other hand, some of the nasal resonants are down below 200. We have therefore to deal with a rather long and formidable range of resonances. Now a word as to amplitude. In "t," "d," "p," "b," "k" and "g" the difference between each of those is only, or almost only, one of relative amplitudes. The resonances themselves are practically the same. The reproducer must therefore be faithful also to rapid changes of amplitude as well as to rapid changes of frequency. It is the high frequencies and the rapid transients which form the difficulties of speech and the difficulties of interpretation. The system must therefore be sensitive, not merely to those frequencies from 2 500 up to about 6 800, but also, for the sake of the vowels, from 200 up to 2 500. I feel confident that if faithfulness of that type can be obtained the amplitude may be enormously reduced without loss of intelligibility.

Captain B. S. Cohen: As an independent observer who has had occasion to test many of the different types of loud-speakers on the market, I may perhaps be permitted to make a few remarks on the present state of the loud-speaker. At a meeting of this Institution in the early 1900's Sir Oliver Lodge demonstrated his hornless loud-speaker, which consisted of a moving-coil electromagnetic system coupled to a wooden diaphragm, and I think it will be agreed that the articulation of that device was of a very high quality. A small number of loud-speakers of the present day are operated on this principle, but Lodge's thin and large wooden diaphragm is presumably considered uncommercial and its replacement by a metal diaphragm and the addition of a horn has not been particularly

advantageous. The great majority of present-day loud-speakers have diaphragms of the usual pattern, either magnetic and operating direct on the magnetic poles or, in the largest types, linked to an armature. In spite of Professor Scripture's dictum that a diaphragm is unsound, as it is bound to produce a distorted wave-front, and that the correct device is a stiff piston, very few attempts have been made in this direction. Novel types of loud-speakers unfortunately have, so far, generally produced novel types of articulation, i.e. novel to the received wave-form. I should like to supplement what has already been said regarding the fundamental basis of operation. To get perfect articulation we require our loud-speaker to have uniform frequency/amplitude characteristics, and I would define the perfect loud-speaker as one having a ratio of acoustic output to acoustic input of unity at all amplitudes and at all frequencies and combinations of frequencies. The volume is of considerable importance, as a perfect reproduction of, say, an orchestral piece with a volume, however, of only 1/100th the original would be of little artistic and realistic value. We can produce wireless receiving amplifiers with combinations of radio, detector and audio stages which give very reasonably uniform frequency/amplitude characteristics, and we can do the same for wire telephony with combinations of loaded lines, filters and audio-frequency amplifiers. We can also employ in both cases transmitting apparatus that will very fairly follow the frequency/amplitude characteristics of the applied sounds. But what can we do with the loud-speaking receiver? We can tune out the more prominent harmonics by mechanical modifications of the moving system, by acoustic modification in the air chambers above and below the moving system and in the horn, and, lastly, we can apply electrical tuning to the loud-speaker in the form of rejector circuits and filters. But all these devices, if pushed to the point of producing a true uniform frequency/amplitude characteristic, result in the loud-speaker belying its name; in other words, there is no reasonable audio output, and the devices above referred to can only be used to the extent of effecting slight improvements. In some cases it is reasonable to infer that the use of a receiving amplifier with a uniform output will result, with a particular type of loud-speaker, in considerably more distortion of the blasting form than when a non-uniform audio-frequency amplifier of, say, the transformer-coupled type is utilized. Thus, if a loud-speaker has a prominent resonance point at, say, 2 000 periods, and a non-uniform amplifier with a flat peak at, say, 1 500 periods is used, this might give more articulate output than a uniform-output amplifier, and will certainly give a very considerable sound output. All this indicates the importance of fitting the loud-speaker to the amplifier, and in the very few cases where this is deliberately done the results are of a very high order indeed. Many loud-speaker and amplifier combinations which give fairly uniform output from, say, 500 periods upwards, and therefore are very articulate for speech, give a colourless tonal quality to music in consequence of the rapid falling-off in output at frequencies below 500, and this is a point to which I think serious attention should be drawn. I would suggest as a very fruitful field for experiment the combination of three or four loud-speakers used simultaneously and each tuned to exaggerate slightly a different portion of the audio spectrum. It is obvious that the frequency/amplitude characteristic of loud-speakers, and indeed of any telephonic apparatus, is of fundamental importance, and apparatus for the measurement of this characteristic is becoming essential in the research laboratory. I have brought to this meeting some apparatus which has been developed for this purpose and I shall now describe and demonstrate it. The device consists of a heterodyne oscillator and high-frequency amplifier coupled to a detector, low-pass filter and audio-frequency amplifier. The combination gives a constant output over the audio range of about 50–5 000 periods, and the whole range is obtained by rotating an air condenser through 180°. This condenser is placed in a light-tight box provided with a shutter and has a cylinder, carrying negative paper, attached to it. If the frequency/amplitude characteristic of a loud-speaker, for example, is to be obtained, the loud-speaker is fed from the oscillator and its output recorded on the negative paper by a non-resonating microphone transforming the received sound into current and recording on the negative paper by means of a suitable galvanometer. The rotation of the condenser dial by hand through 180° produces the complete frequency/amplitude characteristic of the apparatus under test. Constant output is obtained by using variable resistance and inductance combinations for coupling the audio-frequency amplifier.

[Captain Cohen then gave the following demonstrations: (1) Output of oscillator and its amplifier to give constant frequency/amplitude characteristics; (2) output of an ordinary form of two-stage transformer-coupled audio-frequency amplifier, with very small output at low and high frequencies; and (3) motional impedance component of a loud-speaker indicated by horn effect and hand effect at resonance points.]

Mr. G. H. Nash: I should like to put forward some practical considerations in connection with a fundamentally important part of any loud-speaker, i.e. the coupling between the vibrating mechanical system and the air. Professor Rankine remarks: "Of horns I will say no more than that they ought, if at all possible, to be dispensed with . . . because of their resonant character." Captain Eckersley, also, has demonstrated a loud-speaker having a large diaphragm and no horn, and has claimed that this receiver brings out the lower tones so often lacking in other loud-speakers. Let us consider the large diaphragm. It is inherently an inefficient arrangement; it has great mechanical impedance directly coupled to small air impedance. It is true that receivers of this type bring out the low frequencies very well, but the diaphragm coupling is actually less efficient at low frequencies than at high frequencies, and a good low-frequency output in practice is achieved by having a low resonance point. Such a receiver therefore possesses as much resonant properties as a horn receiver; in fact, the low frequencies are overdone and the damping is so low that crisp, staccato effects are spoiled. The reproduction of low frequencies is not therefore an intrinsic virtue of the large diaphragm;

in fact, the same result can be secured with a horn if the diaphragm behind the horn is loaded sufficiently to have a low resonance frequency. Something might be done on the principle of the large diaphragm, if it were not inherently inefficient. Experimental work indicates that the wave-forms of speech or music have peaks somewhere between 5 and 10 times the R.M.S. value, and in music there occurs also a wide range of intensity; this means in practice that for the best results the last valve in the amplifier should have fairly low impedance and should be used with about 6 volts on the grid and 100 volts or more on the plate when an efficient loud-speaker is used. The use of an inefficient instrument, such as the large-diaphragm type, requires not only that more valves must be used, but that the last one must be capable of a greater output of undistorted power. Now consider the horn; it is physically a scientific and proper coupling between the

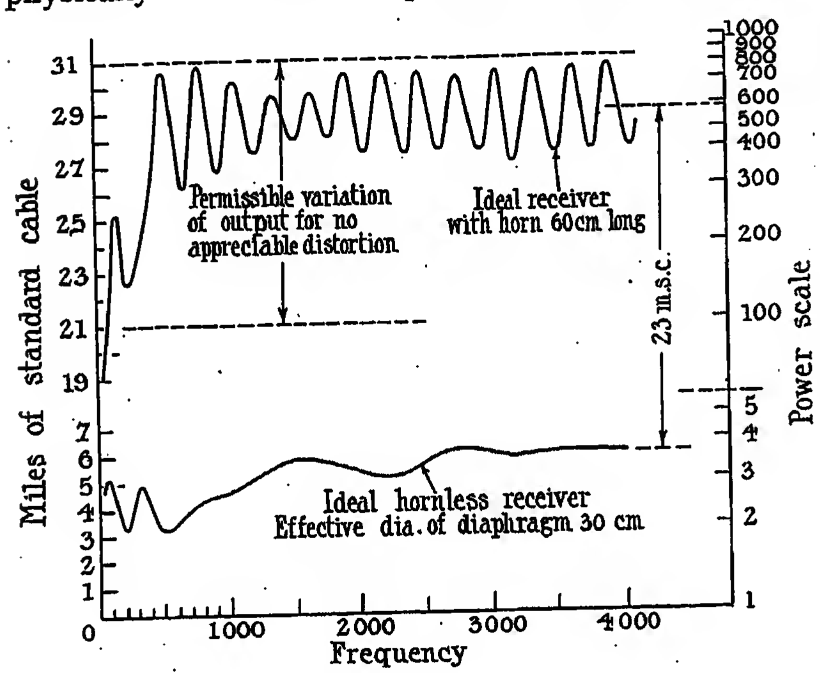

FIG. A.

impedance of the mechanism and the air; its only fault lies in the necessity of compromising between a length that would be ideal and a length that is convenient. Let us see how serious the reputed resonance effects of the horn really are. Fig. A shows the calculated sound-power output from a large weightless diaphragm for varying frequency when a constant force is acting. The upper curve shows the output from a horn of reasonable length, having the same diameter at the large end as the diaphragm and with the same force supposed to be acting at the small end. It will be noticed that the given force produces about 150 times as much power through the horn as it does when applied direct to the diaphragm, and the resonance effects of the horn are really not at all important. It has been well established that distortion within the limits indicated by the dotted lines is quite negligible, and the resonances of the horn are seen to be well within these limits. Further, the resonances can be reduced in amplitude and the output at low frequencies increased by using a longer horn. I contend, therefore, that horns are by no means to be discarded; on the contrary, they *must* be used if good results are to be obtained with a reasonable number of valves of reasonable power, and if a horn is properly designed it does not introduce serious distortion and is not responsible for distortion effects for which it is often blamed.

Captain H. J. Round: If we take any microphone and attempt to magnify the resulting currents, we are very quickly led to recognize the limitations of the amplifying apparatus. A valve amplifier can be stated to have certain peak-voltage limits. Distortion in a valve is generally produced by two effects: the curvature of the plate current characteristic, and the voltage-drop due to the grid current; and in order to exclude these the peak voltages of the microphone current which have to be magnified must not exceed certain values. By increasing the size and power of the valves we can increase this voltage limitation, but there is one place in the system in which this cannot be done economically, and that is the place where the maximum power is used, namely, in the wireless transmitter itself. The consideration of the effect of this is exceedingly complex. The natural sounds which we desire to transmit have all sorts of peak amplitudes, at all sorts of frequencies, but I shall now only consider the question of what basis to adopt for transmitting these different frequencies. The difficulty is this: Suppose we have a microphone which can deliver voltages at the end of our amplifier for all frequencies proportional to air amplitude, or proportional to air pressure, or proportional to some arbitrary scale. What would be the result? It will be admitted that, provided the law were known and moderately simple, we should merely have to apply at the receiving end an inverse to reproduce the original sounds, if no other considerations such as wireless interferences, etc., entered. Unfortunately, however, they do enter: the adjustment of the microphone may be such that the low notes occurring in nature produce 10 volts, whereas the high notes produce 0·1 volt, so that our valve transmitter will be fully used for the low notes and used hardly at all for the high notes. This is very important at the receiving end, for really we are getting 1 kW, say, for middle C and 0·001 kW for the piccolo. Admittedly, given no atmospherics and no valve noises, this difficulty can be overcome, but in general these interferences will be of the same amplitude at all frequencies, and we should have the same ability to hear all the frequencies over the interferences. What exactly does this mean? On the microphones and amplifiers in use now, it is possible to make a very large number of changes in the way the frequencies are represented. Experimentally, I have tried a large variety of sounds such as orchestras, singers, speakers, etc., and I have set the microphone adjustments so that on a variety of ordinary receiving apparatus, such as telephones and loud-speakers, the results are loudest and on an average satisfying, and I have then measured what my microphone is doing. Very approximately equal amplitude of modulation is being given to the transmitter from 200 frequency to 5 000 frequency for sounds of unity audibility, taking as a standard the average of a number of observers. What one might call the tilt of the scale has to be altered a little for various situations, such as different rooms; but in face of other

serious difficulties, which I shall mention, this is a small matter. The sound experts will certainly object to unity audibility, but actually it is at the moment the easiest thing to get without complex apparatus. They will cite the recent work of Fletcher, published in the *Journal of the Franklin Institute*, on the masking effect of low tones on high tones, the meaning of which is really that no complex tones ever sound the same unless the strength remains the same to one's ears. This masking effect is extremely marked and at present prevents any attempt to get a perfect reproduction with a different strength from that of the original. I shall now refer to the use to which we put this. I have a very simple piece of valve apparatus which will deliver pure notes at any frequency and amplitude. I insert these currents into my telephones or loud-speaker and I plot a curve between voltage applied and frequency for just audibility. Curve 1 in Fig. B represents one of these curves for a pair of quite ordinary telephones, and the resulting effect on audibility (neglecting masking effects) is illustrated in curve 2.

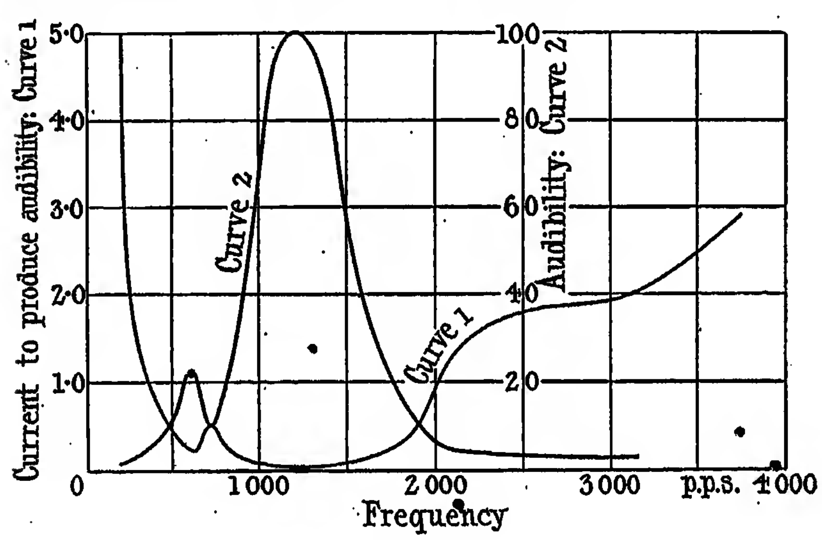

Fig. B.

The meaning of this is as follows: 2LO, received by a receiver in which there is no appreciable electrical distortion, on those telephones would give audibilities for the different frequencies as represented in the curve, instead of equal audibilities. If we try an experiment with that particular pair of telephones and insert in series with them a sufficiently damped rejector circuit so as to flatten out that curve very considerably, although we shall have reduced the total noise we shall quickly understand what fine quality we have missed without it, and we can increase the total sound much more than before without hurting our ears. Moreover, that annoying room echo in some transmissions is considerably reduced. Probably before long it will be possible for the National Physical Laboratory or the British Broadcasting Company to give us a frequency strength standard and then the difficulties of obtaining the audibility curves of our receivers will be less. I have taken up this question of what is being transmitted, and a simple case of its action on a telephone, to show those who are designing telephones and loud-speakers what the input is with which they have to work.

Mr. W. J. Brown: At the last meeting Prof. Fortescue drew attention to the necessity for using in the last stage of an audio-frequency amplifier a valve of considerable output, operating at an anode voltage of the order of 200. From the point of view of the broadcast listener the extra expenditure involved by the use of such high anode voltages is a serious item, while the use of a valve having a large electron emission causes an undesirable drain on the filament batteries. Hence it is of great interest to know exactly how much power a given valve operating at a given anode voltage is capable of delivering to an output circuit such as a loud-speaker without introducing distortion in the valve; this may be termed the "maximum distortionless output." In this connection the orthodox power rating of a valve is extremely misleading; for instance, a so-called 20-watt valve will be found to have a maximum distortionless output of only 0·01 to 0·1 watt, using an anode battery of 120 volts. In course of time, valve manufacturers will probably state the exact amount of power which their valves are capable

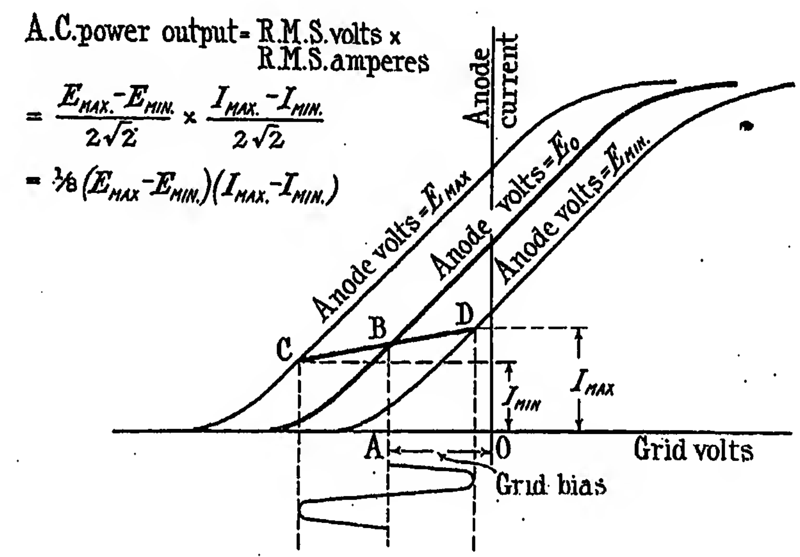

Fig. C.

of handling without distortion when operating at some standard anode voltage, but at present the user of a valve has to make his own calculations and I propose to develop a very simple formula whereby the maximum distortionless output can be calculated. The method has probably been used before, but apparently has not been published. The following assumptions are made: (1) That the output circuit is purely resistive—this, of course, is by no means true, but the case of reactive loads will be considered later. (2) That the waveform is sinusoidal. Though this, strictly, is only applicable to the case of a sustained pure note, the formula will apply equally well for comparative purposes to any wave-form. Suppose that the anode battery voltage is E_0, and that the thick-line curve in Fig. C represents the (anode current)/(grid voltage) characteristic of the valve at this voltage. Choose now a value of grid bias, say, OA. This gives the operating point B on the characteristic. If the a.c. voltage applied to the grid has the magnitude indicated in Fig. C, the operating point will move along some line such as CBD. The anode current will vary from $I_{min.}$ to $I_{max.}$, while the anode voltage will vary from $E_{max.}$ to $E_{min.}$ due to the resistance of the valve. The current

will attain its maximum value at point D at the same moment as the voltage reaches its minimum value. The a.c. power delivered to the resistive output circuit is obviously equal to the product of the R.M.S. anode current and the R.M.S. anode voltage, the alternating

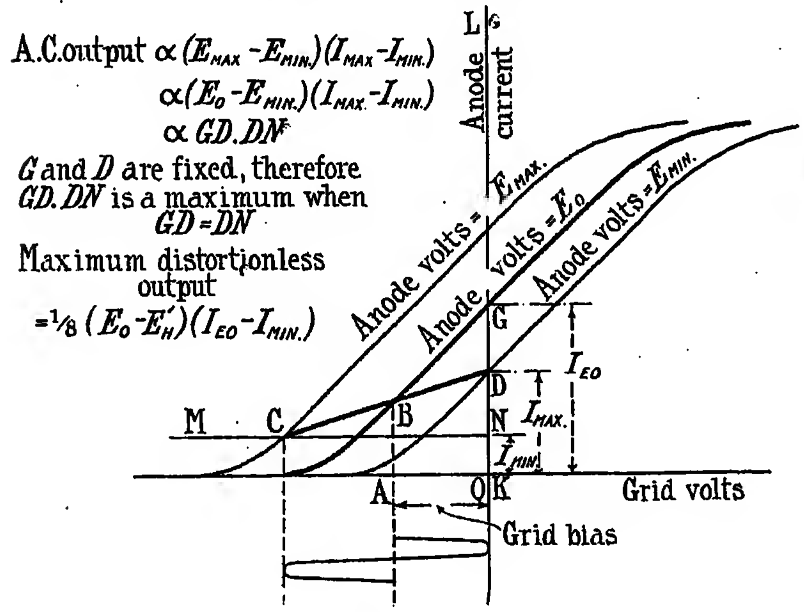

FIG. D.

components only being considered. When the valve is working along the line CBD this power is equal to

$$\frac{E_{max.} - E_{min.}}{2\sqrt{2}} \times \frac{I_{max.} - I_{min.}}{2\sqrt{2}}$$
$$= \tfrac{1}{8}(E_{max.} - E_{min.})(I_{max.} - I_{min.})$$

By increasing the length of the line CBD we can increase the power output. In practice, the length of this line is limited, at the left-hand end on account of curvature of the characteristics, and at the right-hand

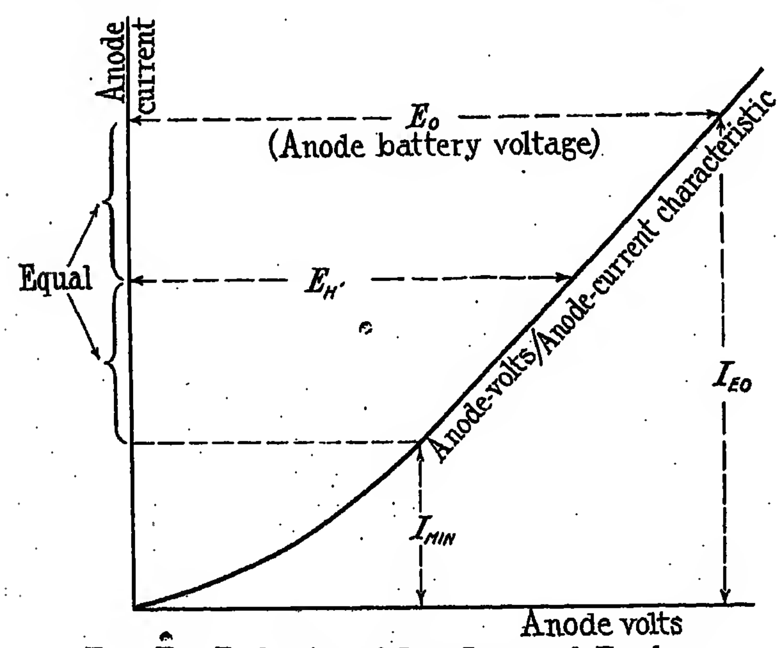

FIG. E.—Deduction of I_{EO}, $I_{min.}$ and $E_{H'}$ from characteristic.

end on account of grid current. In Fig. D the line KL is drawn to indicate the highest grid voltage we may attain without serious grid-current distortion, while the line MN indicates the minimum anode current attainable without curvature distortion. In Fig. D, KL has been drawn through zero grid voltage, while MN has been drawn through the bottom of the substantially straight portion of the characteristic. For maximum distortionless output, the extremities of the line CBD will lie on the lines MN and KL respectively. The problem is to find the conditions for maximum power, and then to calculate the power output under these conditions. As shown before, the power output is proportional to $(I_{max.} - I_{min.})(E_{max.} - E_{min.})$, or otherwise to $(I_{max.} - I_{min.})(E_0 - E_{min.})$. But $(E_0 - E_{min.})$

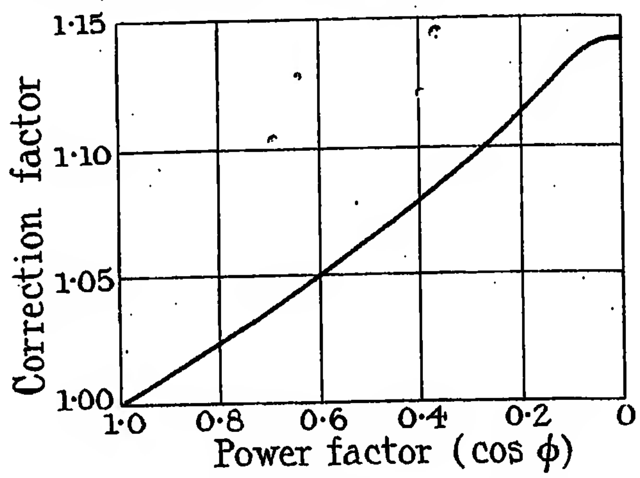

FIG. F.—Correction factor for formula
Max. distortionless output $= \frac{1}{8}(E_O - E_{H'})(I_{EO} - I_{min.}) \cos \phi$.

is proportional to GD in Fig. D, while $I_{max.} - I_{min}$ is equal to DN. Hence the output is proportional to the product of GD and DN. Since the sum of GD and DN is constant, the product, by a well-known theorem, has a maximum value when GD = DN. If a is the differential anode conductance of the valve, then GD on the current scale $= a(E_0 - E_{min.}) = \frac{1}{2}a(E_{max.} - E_{min.})$,

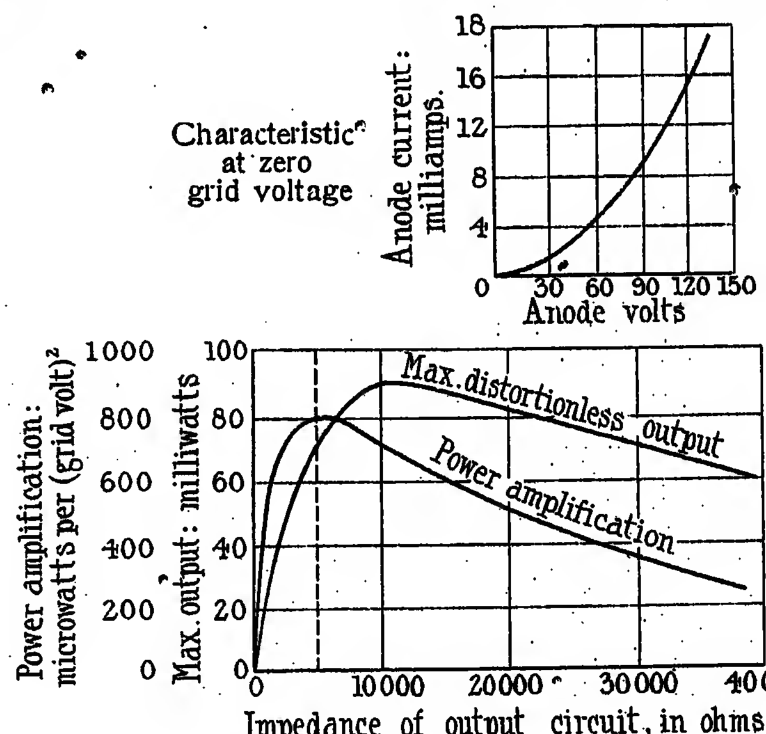

FIG. G.—Output and amplification curves of typcal power valve. Anode battery voltage 120.

while DN $= (I_{max.} - I_{min.})$ to the same scale. The condition for maximum output is therefore

$$I_{max.} - I_{min.} = \tfrac{1}{2}a(E_{max.} - E_{min.})$$

But $(E_{max.} - E_{min.})/(I_{max.} - I_{min.})$ equals the resistance R of the output circuit. Hence $R = \frac{1}{2}a$ is the required condition. In other words, the resistance of the output

circuit must be so adjusted that it is twice the anode resistance of the valve. We will assume that the output resistance is adjusted to this value, and proceed to calculate the maximum distortionless output under these conditions. Returning to Fig. D, let I_{E0} be the anode current at normal anode voltage E_0 and at the limiting positive value of grid voltage (in this case,

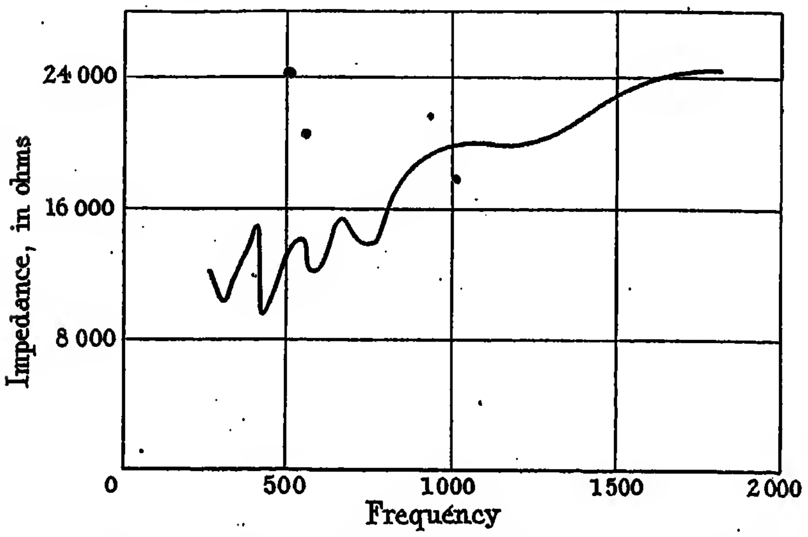

FIG. H.—Impedance/frequency curve of loud-speaker A. Testing current 2·0 mA; resistance 49·25 ohms at 20°C.

zero grid volts). Let $I_{min.}$ be the minimum anode current permissible from curvature considerations. Let E_H be that anode voltage which is required to give an anode current of $\frac{1}{2}(IE_0 + I_{min.})$ working at the limiting grid voltage. This is, in fact, the particular value of $E_{min.}$ which brings the point D midway between

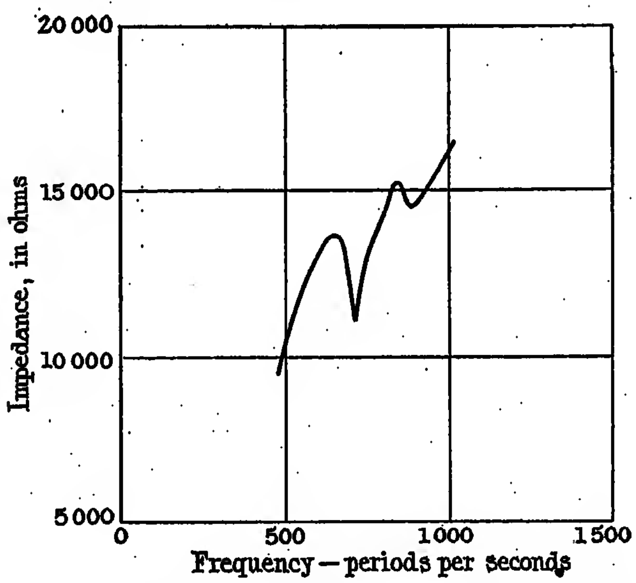

FIG. J.—Impedance/frequency curve of loud-speaker B. Constant current = 2·5 mA.

points G and N. The maximum distortionless output obtainable is then

$$\tfrac{1}{8}(E_{max.} - E_{min.})(I_{max.} - I_{min.}) = \tfrac{1}{4}(E_0 - E_{min.})(I_{max.} - I_{min.})$$

But $(I_{max.} - I_{min.}) = \mathrm{ND} = \frac{1}{2}\mathrm{NG} = \frac{1}{2}(IE_0 - I_{min.})$ and $(E_{min.} = E_H)$. Hence *maximum distortionless output* $= \frac{1}{8}(E_0 - E_H)(I_{E0} - I_{min.})$. Having chosen E_0 the anode battery voltage, the remaining three quantities IE_0, $I_{min.}$ and E_H, may be read directly from the (anode volt)/(anode current) curve, taken at the limiting value of grid voltage, as shown in Fig. E.* We read off I_{E0} directly from the curve, at the point corresponding to E_0, while $I_{min.}$ is selected from curvature considerations. E_H is the length of the abscissa corresponding to the current $\frac{1}{2}(IE_0 + I_{min.})$. No other data are required, so that the method has the advantage of extreme simplicity. The problem of an inductive load is more complicated and there is not time to work it out here. The line CBD of Figs. C and D becomes an ellipse, and we find that the maximum distortionless output is approximately equal to the expression obtained for the resistive case, multiplied by the power factor. The formula thus becomes $\frac{1}{8}(E_0 - E_H)(IE_0 - I_{min.}) \cos\phi$. In other words, the maximum distortionless output expressed in volt-amperes is more or less independent

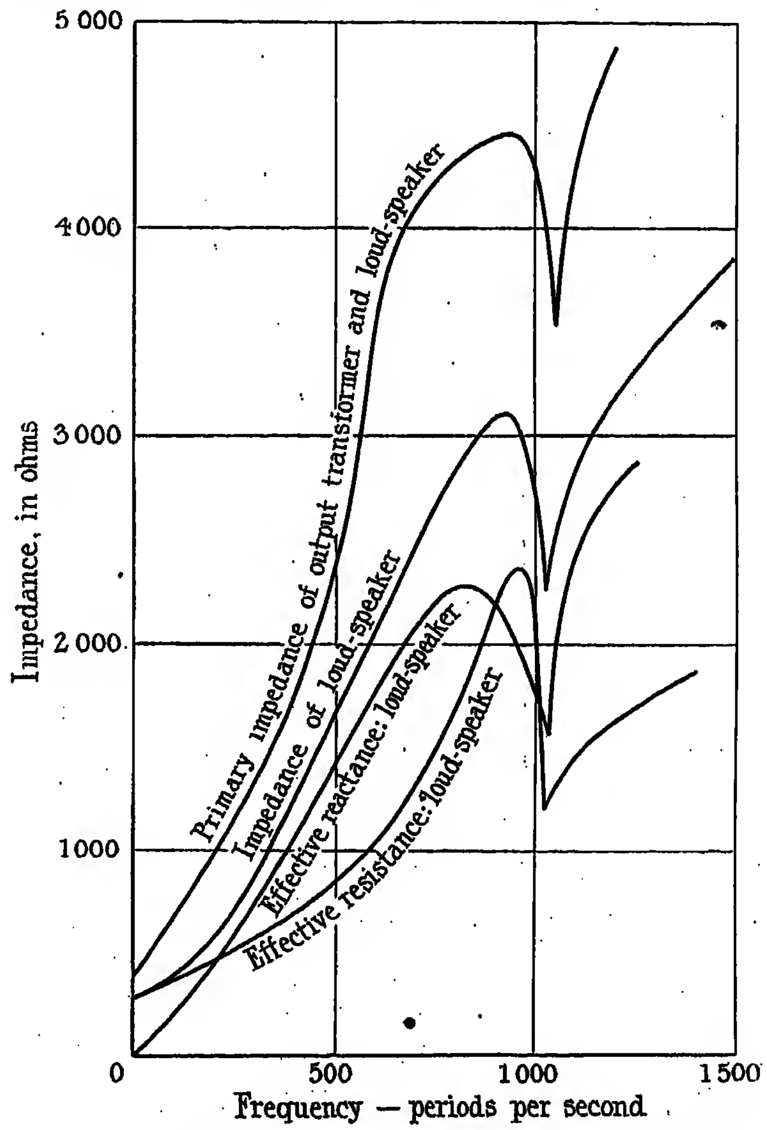

FIG. K.—Impedance/frequency curves of loud-speaker C. Constant current = 5 mA.

of the power factor. Strictly speaking, the figure obtained is rather more favourable for low power factors, and at power factors in the neighbourhood of zero about 14 per cent may be added to it. Fig. F shows the correction factor plotted against power factor. It is interesting to note that the output impedance must be equal to twice the anode resistance in order to obtain maximum distortionless output. On the other hand, the condition for maximum power amplification is met by making the output impedance equal to the anode resistance. Thus we cannot have maximum distortionless output and maximum amplification at the same time. Fortunately, the impedance adjust-

ment is not very critical. Fig. G shows the relative importance of the impedance adjustment for the two cases; this refers to a valve of 5 000 ohms anode resistance. Table A shows the output and amplification obtainable from three typical loud-speaker valves for the two optimum valves of impedance, using an anode battery of 120 volts. The very low value of the output figures will be noted: they vary from 0·27 to 0·086 watt, though the orthodox rating of these valves is of the order of 10 watts. In practice, the adjustment of the impedance of the loud-speaker to suit that of the valve is carried out by using an output transformer of suitable ratio or by suitably adjusting the windings of the loud-speaker. Only a very rough approximation can be made, due to the very wide variation in impedance of the loud-speaker as the frequency is altered. It is thus fortunate that the adjustment of this impedance to suit the valve is not very critical. Figs. H, J and K show impedance/frequency curves of typical loud-speakers and illustrate the amount of variation which may be expected. It will be noticed that these curves have very pronounced peaks, and each peak corresponds closely to a frequency at which the loud-speaker resonates. In fact, this forms a very simple method of detecting the resonant frequencies of a loud-speaker. Returning, in conclusion, to the calculation of the maximum distortionless output of a valve, the formula deduced—and indeed any formula—would depend on the values chosen for the limiting maximum grid voltage and for the limiting minimum anode current. These values can best be found by aural estimation, using a cathode-ray oscillograph for determining the limiting values reached. Prof. Fortescue has shown some cathode-ray oscillograms representing amplifier distortion. It would be interesting to hear whether he has investigated the amount of distortion, particularly of the grid current and of the curvature varieties, which may be introduced into an amplifier without detection by the human ear.

Mr. A. H. Davis: Given physical measurements of the output of loud-speakers, it remains for us to interpret the meaning of the results in terms of the effect on the human ear. Unfortunately, sufficient data for this are not available. It is, however, desirable to consider some of the acoustic determinations which enable us to appreciate the range of the ear and the way it behaves, and especially to consider those which throw light upon any side of the question of distortion. In normal conversational speech the pressure amplitude in the sound waves at 1 ft. from the mouth appears to be about 1 000 times as great as the minimum necessary for audition, and about 1/1 000th of the maximum that can be reached before tickling sensations and pain supervene in the ear. The total range of audible amplitudes is thus about a million-fold. It assists in appreciating these figures to note that persons not ordinarily called deaf may require up to 100 times the normal "threshold" value, and those who need a further hundred-fold increase are sufficiently deaf to require an ear trumpet. With respect to the capacity of the ear for detecting differences of loudness, it just discriminates between two successive notes of the same pitch when the amplitudes of vibration differ by 5 per cent. Thus equal increments of sensation result from equal increments in the logarithm of the stimulus. It is thus useful to plot intensities logarithmically. The figure of 5 per cent is, however, increased for faint sounds. It is found from these data that the million-fold auditory range can be covered in not more than 270 steps of increasing loudness, each one just perceptibly louder than the former. A two-fold amplitude change is equivalent to about 14 such steps, a hundred-fold to 94. The loudness of speech has some bearing on its distinctness, which is best for the medium level (1 dyne/cm^2) of normal conversation. Ten-fold increase or decrease in amplitude is almost without effect, but decrease to 1/100th reduces articulation by about 50 per cent. We find that consonants are more seriously affected than vowels by reduction of speech intensity. As stated by Sir Richard Paget, some of them are carried by very high frequencies, and in ordinary conversation 50 per cent of mistakes of interpretation can be traced to three of them alone. In these circumstances, and seeing that

TABLE A.

Maximum Distortionless Output in Milliwatts, and Power Amplification Factor in Microwatts per (Crest Grid Volt)^2.

(1) With output circuit impedance adjusted for maximum amplification, ($Z = 1/a$).
(2) With output circuit impedance adjusted for maximum distortionless output, ($Z = 2/a$).

Valve	$Z = 1/a$			$Z = 2/a$		
	Z	Amplification	Output	Z	Amplification	Output
	ohms	μW/V²	mW	ohms	μW/V²	mW
A	4 720	802	58	9 440	713	86
B	8 350	488	39	16 700	434	44
C	10 300	392	27	20 600	348·5	30

experience leads public speakers actually to emphasize their consonants, it is surely unfortunate that loud-speakers become weak at high frequencies. It must surely limit their use in acoustically difficult conditions unless the electrical system is designed to effect some compensation. With further reference to speech, the falling off of loud-speaker efficiency at frequencies less than 300 should have little effect on distinctness, but some change of character or raising of the pitch is to be expected. The normal male voice has a very pronounced low-pitched constituent of frequency about 120, and the female voice has one about an octave higher. To reproduce speech and to preserve all its characteristic qualities, frequencies from 100 to above 5 000 must be delivered with approximately the same efficiency. The amount of distortion permissible in reproduction of speech or of music will naturally depend upon circumstances, and no accepted criteria seem to be available. However, judging from threshold values —and there is some evidence to indicate that we may do so—there are certain imperfections in individual ears which probably set a limit beyond which accuracy of reproduction need not be carried. It is found that, although the average of several normal ears has fairly smooth sensitivity over the frequency range, the threshold sensitivity of a normal individual ear is not uniform, but exhibits maxima and minima at various frequencies peculiar to that particular ear. In a typical case, from two-fold to six-fold variations occur as the frequency range is covered. Different individuals have quite different characteristics, so that, apparently, music does not sound the same to different persons. Consequently, while the effect of distortion within, say, a two-fold limit might be detected, probably there would be divergencies of opinion as to whether improvement in quality had been effected. The *minor* peaks and resonances exhibited by the best loud-speaker curves appear to fall very near to the minimum thus indicated as the least distortion that normal individual ears could fully appreciate.

Mr. A. J. Aldridge : I wish to give some quantitative information in regard to the orders of magnitude occurring in loud-speakers, and to draw attention to a fundamental error which appears in many commercial instruments. Fig. L shows the diaphragm motions of a number of commercial loud-speakers operated with different inputs. The first point to be noticed is the very small extent of the motion. An average of about 0·05 watt in most loud-speakers will give sufficient volume comfortably to fill a normal private dwelling room, though this does not mean that this figure may not be considerably increased on individual notes. The corresponding diaphragm motion is usually less than ½ mil. Curves (*a*), (*d*) and (*e*) are for instruments constructed on the lines of an ordinary receiver, i.e. with a plain iron diaphragm. It will be noticed that the inwards motion considerably exceeds the outward for the same input [in the case of (*e*) by 30 per cent, with an input of 0·05 watt]. This means that very serious distortion, producing harmonics, will occur, and would appear definitely to bar this type of instrument for accurate reproduction for any but small inputs. Curve (*b*) is for a moving-coil instrument, and curve (*c*) for one with a balanced armature. The apparent greater efficiency of this latter model is probably due to the method of test. Direct current was used, and this makes no allowance for unavoidable losses due to slight slackness in the linkages used in this type of instrument. I have intentionally omitted any mention of resonance, which is dealt with by other speakers, but in selecting a loud-speaker it must, of course, be considered. Resonance is undoubtedly serious, but can be corrected, whereas the fault to which I have referred would appear to be only capable of correction by the use of a larger diaphragm and smaller motion, or the use of a larger air-gap, with corresponding increase of power. I think that insufficient attention has been paid to irregular diaphragm motion, which

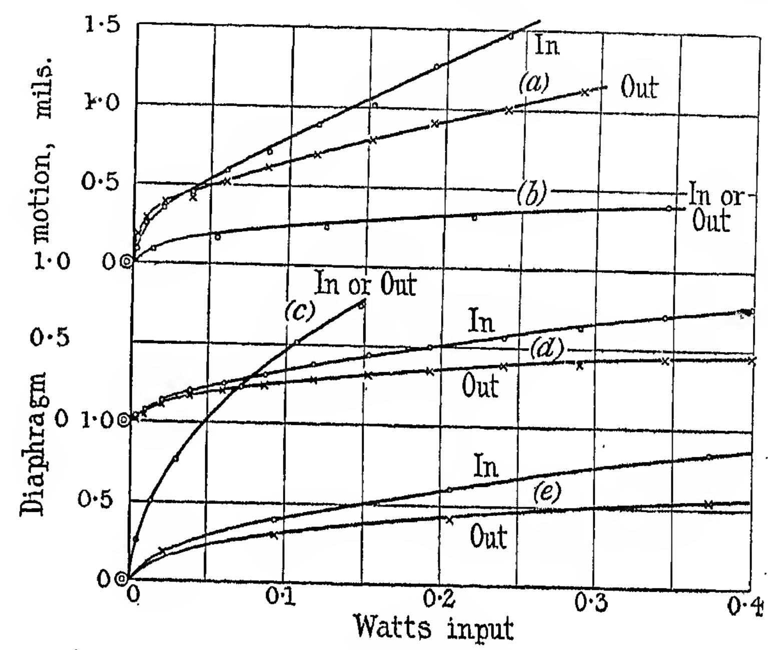

FIG. L.—Diaphragm movements in loud-speakers.

probably accounts for much of the faulty reproduction and poor tone appearing over the whole gamut of frequency unless very small amplitudes are dealt with.

Captain N. Lea : Prof. Rankine draws attention to the danger of reaction complications when a forced vibration begins to influence the form of the forcing vibration. The possibility of this happening in the mechanical parts of the system has probably been less obvious to those engaged in wireless research than that it should occur, for example, in the last stage of a thermionic amplifier. Prof. Rankine points out in his concluding remarks that in testing results it is not much use to attempt to obtain simultaneous visible records of the sound source and sound image (if one may use such an expression), because of the difficulties of attaining exact results and interpreting them in their audible equivalents. Nevertheless, in view of the fact that, as we approach more and more to fidelity of reproduction, audition becomes an increasingly difficult test to apply, I think that the process of feeding sensibly pure sine oscillations into the apparatus under test, and of watching the results by instrumental means as the frequency of the oscillations is varied, must always be followed. Prof. Fortescue has described some of the difficulties of amplifier design, but he has not exaggerated them because he has taken no account of the limitations imposed upon any design intended

to cater for the domestic user. It is, for example, impossible to expect the music-lover to fill his house with high-voltage batteries, and it is taking some time to persuade people to use an adequate number of valves which are large enough to ensure good results. In discussing the horn, which forms part of the conventional loud-speaker, no one seems to have referred to the polar distribution of radiated sound energy at various frequencies. I do not know whether other observers have noticed, as I have done on frequent occasions, that even if the frequency balance is good when the ear is in a line with the horn opening, it may happen that a large percentage of the upper part of the sound spectrum is missing when the ear is moved to one side of this line. It may be of interest to describe an arrangement which I have employed with rather pleasing results. The device may perhaps best be described as a spectroscope for audible frequencies. It consists of two main portions, first a rotating spindle for the purpose of controlling the frequency of the oscillations imposed upon the apparatus under test, in such a manner that it sweeps over the whole audible scale during the revolution of the spindle. The spindle has mounted on it a variable condenser of the semi-circular vane type which is connected to one of two high-frequency oscillators employed for the production of beats, which latter, when rectified, are used as a variable-frequency source for testing apparatus within the audible scale. The second part of the device consists of a cathode-ray oscillograph with its auxiliary apparatus. By this means it is possible to cover a very large frequency range without altering the constants of the oscillating circuits by more than a very small percentage, and hence one may be reasonably certain that the amplitude of the beats produced does not vary with their frequency. There is, of course, the risk that this method of setting up a variable-frequency source may give trouble owing to interaction between the two oscillators and also to the departure from sine wave-form of the beats when rectified. It is also necessary to employ a fairly high decrement in the high-frequency circuit attached to the rectifier, in order to prevent a change of amplitude in the induced current when the frequency of one of the oscillators is changed. The application of the beat frequency of the apparatus under test gives rise to an E.M.F. on the output side which can be applied to one pair of deflecting plates in the cathode-ray oscillograph. A rotary potentiometer is mounted on the same spindle as the variable condenser already referred to, and this furnishes an E.M.F. which can be applied to the other pair of deflecting plates for the purpose of spreading out the output indications at various frequencies and thus giving a spectrum band. The potentiometer merely separates the various frequencies in the same way as a prism does in an optical spectroscope. A commutator is also mounted on the spindle in order to prevent a second image being obtained when the condenser is passing through the second half of its revolution, and when, in consequence, the frequency band is traversed in the inverse direction. The spectrum produced consists of an illuminated band, the width of which at any point is a measure of the response experienced at the corresponding frequency. By mere inspection it is possible not only to discover faults in the distribution of response, but also instantly to observe the effect of any steps taken to improve the results. Some speakers have raised the question of the relation between the sensitiveness of the human ear and the frequency impressed upon it. Surely it would be wrong to introduce such a function into the design of a loud-speaker, because it is only by making the output a copy of the original that we can hope to deceive the listener into believing that he is, in fact, listening to the original. Any device for the correction of ear-frequency balance would (like spectacles) have to be a personal matter, and unless the arrangement could be attached to the head it would seem necessary to put the sub-normal listener with his special loud-speaker in a room by himself.

Mr. G. C. Marris: I cannot agree with all that seems to be inferred from the facts given in this discussion. As each speaker has presented his own particular problem, the general effect is that nothing can be done. Perhaps this is true so long as we make no clear decision as to whether we will have more quality or more volume. In other words, ought we not to develop two distinct types of loud-speaker, or perhaps three? These would be, first, a general-purpose instrument, as most of the instruments on the market seem to be. They give plenty of sound for a large private room or for the entertainment of a small private party. They reproduce speech very clearly and give music which is pleasant to listen to for a short time. Only a comparatively small valve is necessary for their operation. The second class would be the new one, and would be a type of instrument working off the largest output valve practicable in a private house, suitable only for use in a small room or by persons sitting close to the instrument, with resonance of every kind suppressed to the lowest limit at the expense of volume and designed to cover a wider range of frequencies. The third class exists already in the instrument used for large halls and audiences. Since a fairly wide range in the matter of power supply is permissible with this type, the problems of design should be simpler, or perhaps it is more correct to say, less obvious. With these possibilities, more particularly Class 2, in mind, I should like to comment on the remarks of some of the previous speakers. Several have suggested that the horn is the ideal form of coupling between the electrical system and the room. It is indeed to be hoped that this is not the case. I have listened a good deal to loud-speakers, and in all cases have become very tired of the horn resonance. That it is horn and not diaphragm resonance is easily proved by removing the horn. If we are to make an electrical analogy it must be to a resonance transformer or a very short transmission line, neither of which is a good coupling device. Further, there is the fact that the actual musical instruments with wider frequency-ranges, such as the violin and piano, have no horn. The other point is in connection with valves. Having had to urge the use of valves of large output, I am very pleased to read Prof. Fortescue's summary of the various forms of amplifier distortion. I should

like to corroborate his remarks in regard to the distortion due to the valve itself. Measuring the characteristics of a valve with a power output of about the maximum practicable for a private set, I found that for about 1 volt (peak) on the grid the second harmonic was 0·4 per cent of the fundamental, while for 5 volts (R.M.S.) on the grid the second harmonic was 1 per cent of the fundamental. If, however, one attempts to obtain under the same conditions so much power out of, say, an R valve, the higher harmonics would be of the order of 50 per cent. of the fundamental. It seems to me, however, that Prof. Fortescue's remarks on page 272 on the output required should be qualified, as otherwise we should have to condemn, I think, unnecessarily a large proportion of existing loud-speaker outfits. Using the ordinary loud-speaker which makes use of horn resonance, an ordinary room can be pleasantly filled with speech or music if a valve having a maximum distortionless output of, say, 5 milliwatts is used. I believe that this power covers 90 per cent of the loud-speakers in use. Here, it seems to me, is the great opportunity for the quieter, better-quality type of loud-speaker referred to above as Class 2. Let us make use of the larger-output valves capable of giving 50 to 100 milliwatts of power with reasonable voltages, but direct this power to the improvement of quality, not of volume. It seems quite practicable to design valves with still larger distortionless outputs at reasonable voltages, but at present there is no loud-speaker which is capable of making good use of such power in a small room. In connection with the formulæ given to-night for output, there is a very simple way of getting the figure from the constants of the valve, pointed out by my colleague, Mr. A. C. Bartlett. If v be the length of the straight part of the valve characteristic on the negative side of zero, at the particular anode voltage applied, then the R.M.S. grid voltage which can be applied to the valve without causing distortion is nearly $\frac{1}{2}v$, and the distortionless power output is therefore approximately $(m^2 v^2)/16R$, where m is the amplification factor and R the anode filament resistance, usually known as the internal resistance of the valve. It is useful to note that $\frac{3}{4}v$ is also the optimum value of the direct-current negative voltage at which to work the grid.

Mr. W. E. Burnand: From what has already been said and demonstrated it is very obvious that there are many other factors connected with loud-speaker reproduction than the loud-speaker itself, and that many faults which are blamed to the loud-speaker may be traced to something else. The extra output on certain notes—similar to what is called the "wolf" note in some violins—can often be traced to the amplifier. One can imagine an amplifier with a tendency to oscillate, working near that point. When a signal comes through of the same frequency the two together will give rise to this "wolf" note. It may be the loud-speaker, but the fact remains that, in many cases, by altering connections or applied potentials it can be got rid of, thus showing that the amplifier and not the loud-speaker is at fault. There still remains the trumpet tone and the various other resonances. Apart from these, I think sufficient prominence has not been given to the effect of harmonics and overtones. All the experiments or curves connecting output with input which have been shown are with pure tones. I think that the overtones and harmonics are of equal importance, even beyond the audible range, in the effect produced by the speaker, since these form beats within the audible range. I was led to suspect this by running two loud-speakers in series, a large Brown and a large Western, about 6 ft. apart, and standing 8 ft. away from them. The input to each was exactly the same, and yet, listening for a period, it was curious how the sound appeared to emanate first from the one and then the other, and how at other times the outputs of the two were approximately the same. It does not mean that one loud-speaker takes charge of the high notes and the other takes charge of the low notes. It seems to be a matter of the timbre quite as much as of the high or low notes, and the timbre is of course due to the various frequencies and harmonics. For instance, the sound of a flute would appear to come from one instrument, and the announcer would appear to speak through the other. The explanation that this might be due to the standing waves is I think also done away with by the fact that one appeared

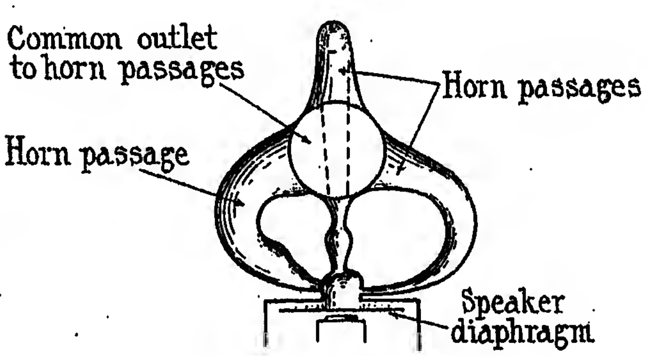

Fig. M.

to take charge for a matter of some seconds, during which a considerable number of notes were sounded, and the position of those standing waves would vary with the note. I think, therefore, that one horn or one air passage cannot be the best thing for all classes of music or all tones, and that it is possible to get a much better result by having either a number of horns or a number of air passages, which might be combined in one outlet. This is shown in rough diagrammatic form in Fig. M, several horn passages of different length and configuration branching out from the sound box and meeting again at a common outlet. I was interested in the demonstration showing the modes of vibration of a diaphragm, but I cannot think that those apply even approximately to a diaphragm such as is used in the Brown instrument with a conical diaphragm, or to the Western with the concentric corrugations, or to the loud-speaker with the radial corrugation shown by Captain Eckersley. Having designed transformers for 30 years and personally evolved some 9 000 different windings, some of which are, of course, now obsolete, I must say that the average transformer put in a wireless amplifier on the low-frequency side is very much worse than might be expected from the firms who, one would imagine,

should know better. On the question of the open circuit compared with the closed magnetic circuit transformer, they both have their defects. For the amplifier a transformer with characteristics lying somewhere between those of the series and the ordinary shunt transformer is required, i.e. both the magnetic and current densities vary, and also there is a d.c. component. With a closed magnetic circuit, that component shifts the flux to one side of the neutral position. Therefore the alternating component of an average of 1 000 frequency must give a distorted output. Going to the other extreme, there is the open-circuit transformer used with a straight core, which, as is well known, requires quite a large magnetizing current. Many papers have been written to show that the output does not then match the input, especially under the conditions used in an amplifier, where the amplitude varies with inductive and capacity reactance as well as resistance. I think, therefore, that for good results something between the two is necessary, i.e. a transformer with a nearly closed magnetic circuit, with an air-gap (a few thicknesses of paper will give sufficient spacing) of 1 or 2 per cent of the length of the magnetic circuit. The old Edison "electro-chemical" telephone was, I believe, the first of the loud-speakers in which the diaphragm vibration was augmented by varying the friction on a revolving element. According to an old book,* this consists of a flat spring, attached to a 4-inch mica diaphragm at one end, pressed by a rubber pad on to the surface of a revolving cylinder of moist gypsum impregnated with potash and mercuric acetate. The spring is made negative. Used with a contact point on the end of the spring touching the cylinder, this is also employed as a transmitter.

Dr. H. M. Barlow: I should like to say one or two words about a novel type of telephone which I am now

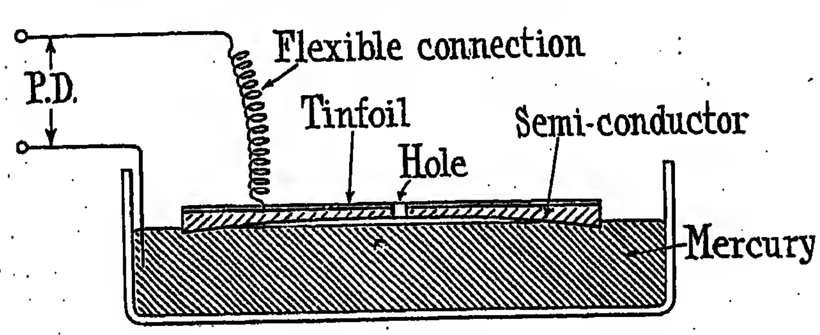

FIG. N.

engaged in developing, and which Fig. N will help to explain. The so-called Johnsen-Rahbek effect, involving the electro-adhesion set up between a solid metal and a semi-conductor which are in contact and have a potential difference between them, is well known, but I do not think it is generally known that the same effect is obtained with a semi-conductor in contact with a liquid metal such as mercury. I made this observation myself some time ago,† and I have applied it to a telephone, among other instruments. Take, for example, a piece of semi-conductor such as lithographic stone or slate, in the form of a thin disc, and make the underside of it concave or convex, so that when floated on a pool of mercury the surfaces do not make contact over the whole area. Cement a piece of tinfoil to the upper surface of the disc, and apply a varying P.D. between it and the mercury. The semi-conductor will then oscillate on the surface of the mercury, due to the variation in the electrostatic forces operating across the interface. If a telephonic voice current is employed, speech is reproduced. An alternative method of producing sound is to bore a small hole through the centre of the disc so that, when it is pulled down, the air is squeezed out of the confined space between it and the mercury. The arrangement has given very good results with a 2-valve receiving set working on 2LO.

Mr. P. G. A. H. Voigt: So far only one or two speakers have said anything in favour of the present-day loud-speaker. One of the accusations which is generally levelled against it is that of chronic inefficiency. I do not believe that the peak of efficiency is much more than 10 times the average efficiency, and I shall now show one experiment to prove that the loud-speaker's efficiency is more than the fraction of 1 per cent with which it is generally credited. It is an experiment which has been known to telephone engineers for many years. It is a kind of Hopkinson test. The power from the loud-speaker, acting as a microphone (quite a good microphone too), is fed through a telephone transformer to the input circuit of an ordinary single-valve note magnifier. The output goes through another telephone transformer to the other loud-speaker, and the sound output is sufficient to maintain an oscillation. If we take the extreme theoretical case of an efficiency for that stage of note magnification of 75 (transformer 5 : 1, valve amplification factor 15), then the efficiency of our loud-speakers is the reciprocal of the square root of that figure, i.e. between $\frac{1}{8}$th and $\frac{1}{9}$th of 100 per cent, say 12 per cent at the most efficient frequencies. If we take a more reasonable figure of 25 for the stage of note magnification, we get a peak efficiency of 20 per cent, which is very far removed from 1 per cent. It can quite easily be shown that it will oscillate on several notes, but there are definite gaps. [Demonstration.] I think those gaps explain the reason why with two different loud-speakers in series the sound apparently wanders from one to the other. There is another efficient point among the lower notes. I expect that one is the air-column resonance of the air in the horn and the first is the mechanism resonance, and I believe that the greater part of the loud-speaker distortion, when the loud-speaker is responsible for it, is due not to the horn but to the mechanism. We have been told that the resonance in a telephone can be compensated for very easily by a suitable, tuned circuit, and we have also been told on good authority on previous occasions that the present-day loud-speaker which is fairly well evened up cannot be so compensated. Recently I listened through my loud-speaker to the opera, and at the end of it I concluded that although the results were very good, they were not quite natural, and I remembered a circuit which I had drawn out in

* "Electricity in the Service of Man" (Cassell and Co.); also see H. M. Barlow: "An Investigation of the Friction between Sliding Surfaces," *Journal I.E.E.*, 1924, vol. 62, p. 183.

† *Journal I.E.E.*, 1924, vol. 62, pp. 143 and 156–158.

May 1922 but had not yet tried. In that arrangement a loaded telephone and a closed telephone—that is, one with the front covered up—were used in a Wheatstone bridge, and instead of having a galvanometer at the junction points I had the primary of a transformer which fed back the difference into the grid circuit, thus attempting to even up the output by balancing the loaded against the unloaded telephone. I tried that arrangement with loud-speakers, but the difference between the two is so slight that it is necessary to feed back several stages to get any change at all, and the result even then is only howling at various frequencies. But with a slight modification; i.e. disconnecting the closed loud-speaker from its transformer and reducing the impedence of that transformer, an arrangement is obtained which I think gives results a little more natural than the usual circuits. [Demonstration.] The effect is best shown when there is a full orchestra, or preferably the opera, in which all the instruments are present. In the 2LO orchestra I understand that the bass instruments are omitted for the simple reason that they do not reproduce. Therefore a loud-speaker which would reproduce them if they were there cannot properly prove its superiority. I can switch over from the compensating arrangement to the other, but that can only give an indication of the change. If it is

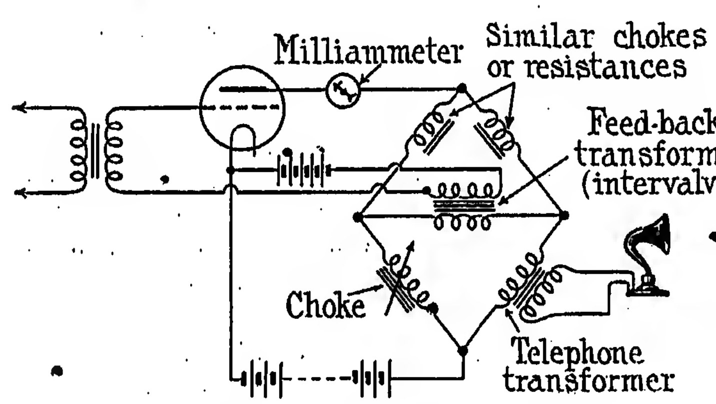

FIG. O.—Compensating circuit.

desired to find out what the difference really is, the characteristics of the loud-speaker must be well known. People ignorant of any change have remarked on the difference although they had not heard the instrument at work for several days. Actually the change-over on the switch does not seem to indicate anything like this difference. I should like to point out that the efficiency is only slightly reduced, and when several people are speaking together the voices appear to come out separately instead of all together. Further, the lower, and sometimes the higher, notes come out better, while the middle notes are suppressed or muffled. The compensating circuit is shown in Fig. O. The musical scale with its harmonics covers 10 or 11 octaves. The ordinary loud-speaker is fairly efficient over the two octaves which are most used (say 300 to 1 200 cycles per sec.). The resulting distortion is most noticeable with a piano. The human voice sounds high-pitched; an orchestra sounds as though the instruments were differently distributed; and most solo instruments sound like similar instruments of different tone. Because of this, the perfect loud-speaker, or a perfectly compensated loud-speaker, will not seem much more natural than those we have at present, unless the reproduced music can be directly compared with the original. After knowing a certain loud-speaker for a long time, however, the ear becomes very sensitive to its imperfections, and notices any improvement at once, although, to a stranger, both reproductions may sound equally perfect. The question of transformer distortion has been raised. I find that with reasonably good transformers the distortion is hardly perceptible even with a compensated loud-speaker. One great difference between a resistance-coupled and a transformer-coupled amplifier is that if we attempt to overload the valves of a resistance-coupled amplifier it shuts down, whilst the corresponding transformer-coupled amplifier distorts. Instead of the operator, it is the transformer or loud-speaker that is blamed. In conclusion, I greatly regret that many firms are now incorporating the parallel condenser in their loud-speakers. This condenser, by reducing the efficiency at the highest frequencies, not only spoils the reproduction but by masking valve distortion encourages users to overload their valves and spoil the reproduction still further.

Mr. C. M. R. Balbi (*communicated*): Professor Fortescue's work on the power amplifier has shown that distortion is not due to the amplifier if the apparatus is properly designed, while others put the blame directly on the diaphragm of the loud-speaking device. The sound pictures of Professors MacGregor-Morris and Mallett are very convincing in this respect, and one feels obliged to agree with Mr. Pocock when he remarks that "Present-day electromagnetic loud-speakers are without exception a compromise between relatively good efficiency and good quality." The main line of attack towards better articulation is to obtain an improved form of diaphragm. One or two practical suggestions have been made to overcome this defect, but those responsible for them seem to admit that they are still a long way from the correct solution. In an attempt to solve this problem I have devised a system in which the inherent inertia and the natural frequency of the diaphragm have been completely eliminated. This is accomplished by vibrating the diaphragm continuously at a slightly supersonic frequency by electrical means, and then producing the required articulation either by modulating the energizing source or by varying the friction between two rubbing contacts to obtain the same result, as in the case of the Brown "Frenophone" or the Johnsen-Rahbek loud-speaker. The active part of the diaphragm of this apparatus may be as much as 8 or 10 inches in diameter. Among the advantages of this system is the fact that a very much larger volume of sound can be controlled by a single unit than has hitherto been possible.

Mr. F. E. Smith (*communicated*): Professor Rankine has suggested that it ought to be possible to make a direct comparison between the original and the reproduced sounds. Such a comparison is possible and can easily be made by means of an oscillograph if the latter enables two records to be made simultaneously. In practice the speaker (or source of sound) and the receiver should be housed in the same building, an easy matter

to arrange in the 2LO station. In addition to the oscillograph, two telephone receivers, as identical as possible, would be needed; these receivers should be connected to the oscillograph and when a sound is made in front of them the two traces should be practically identical. Distance and echoes must, of course, be taken into account. In an experiment with speech the speaker would broadcast as usual, but one of the telephone receivers would be placed near the transmitting microphone, and the other would be acted on by the reproduced speech from the loud-speaker. Two oscillographic records would thus be obtained, one corresponding to the original and the other to the reproduced sound. The difference between the two records would be due to the distortion produced in the link, made up of microphone, amplifier, transmitting set, receiving set and loud-speaker. Such an experiment has not to my knowledge been made, but it presents no great difficulty. I have taken many speech records with oscillographs and obtained excellent results. Records of speech would not be very useful. A good plan would be to have fairly pure tones from tuning forks varying in frequency from 50 to 5 000. At first, single tones should be transmitted, but afterwards it would be well to transmit two notes simultaneously. Differences in amplification should not be difficult to detect by analysis of the resultant curves.

Mr. L. W. Wild (*communicated*): I desire to discuss in some detail a cause of tone distortion which is very generally met with and which I consider has not yet received adequate attention. It is common practice to operate a loud-speaker by means of two low-frequency valves. It is the distortion occasioned by the valve coupling that is in my opinion the worst offender in receiver design. This coupling is generally effected by means of an iron-cored transformer with a moderate step-up ratio. The standard pattern of transformer has a primary inductive impedance of about 10 000 ohms on 260 periods (middle C). The valve preceding the transformer has an internal impedance round about 100 000 ohms. An unloaded transformer working below its resonance frequency (about 1 500 periods) may be considered to be a simple inductance. The valve impedance may be considered to be simply a resistance. We thus have a resistance in series with an impedance, the former being the predominant partner at all frequencies below resonance. An inductance has the property that its current and E.M.F. waves are different in form, unless both are pure sine waves. Every harmonic present in the current wave is intensified in the E.M.F. wave. For example, a third harmonic in the current wave comes out exactly three times as strong in the E.M.F. wave. It follows from the foregoing that on all fundamental frequencies except for about one octave near the resonance point, the harmonics in the current wave will be substantially the same as in the E.M.F. wave impressed upon the grid of the first valve and, in consequence, the harmonics in the E.M.F. wave impressed upon the transformer and passed on to the grid of the second valve will be greatly intensified, thus causing tone distortion. Could, however, the inductive impedance of the transformer be greatly increased so that throughout the musical scale it was several times the impedance of the preceding valve, we should have an E.M.F. wave impressed upon the grid of the second valve substantially similar to that impressed upon the grid of the first valve, with practically no tone alteration. I have worked out a design for a transformer having an even ratio and an inductive impedance of 2 megohms on 260 periods, or about 20 times the impedance of an average valve. The weight of this transformer would be 40 lb., and I am afraid that it would not be considered an ornament in the drawing-room. But why use a transformer at all? A simple inductance constructed on the same lines but without a secondary winding can be made having the desired impedance and not weighing more than 5 lb., which is, I think, within the limits of size, weight and cost requisite to meet with approval. I have made several of these inductances and have distributed them amongst my friends, all of whom report that by substituting these for their former transformers they have effected a marked improvement in tone reproduction besides obtaining an increase in volume of sound. The increase in volume is no doubt due to the fact that full advantage is taken of the amplification factor of the first valve, which is not the case with a transformer, and is not compensated for by the step-up ratio. These inductances have an inductive impedance of 2 megohms and a capacitative impedance of rather over 4 megohms on 260 periods. Their impedance is therefore several times that of the preceding valve over the whole range of the piano scale. The same tone reproduction can be obtained with the well-known but little used resistance coupling, but under the best conditions the amplification realized with this form of coupling cannot exceed half that obtained with inductive coupling if the same number of high-tension cells are used. Because I condemn the employment of transformers for valve coupling it does not follow that I cannot find a place for them in some part of a receiver. A potential transformer following a crystal and preceding a valve is a perfectly legitimate appliance to use, provided that no high-frequency amplification is employed. A treated galena crystal has an impedance of only about 400 ohms, and if the transformer has a low primary resistance, an impedance of about 10 000 ohms on 260 periods and not too much self-capacity, there should be practically no tone distortion. To design a potential transformer free from tone distortion for employment in this position is not difficult. What is more difficult is so to adapt the design as to obtain the maximum volume of sound, and, for this purpose, consideration has to be given to the oscillating circuit from which all power must be drawn. Most of our present transformers are fairly efficient in this respect but could probably be improved somewhat by about trebling their weight.

[The replies of the authors of the introductory papers will be published later.]

INSTITUTION NOTES.

Faraday Medal.

At the Ordinary Meeting held on the 31st January, 1924, the President announced that the third award of the above Medal had been made to Dr. S. Z. de Ferranti, a Past President of the Institution.

George Montefiore Prize.

The 1923 award of the above prize has been postponed to 1925, the last date for the receipt of papers being 30th April, 1925. Full particulars of the prize, the value of which on this occasion will be 22 500 francs, can be obtained from the Secretary, Association des Ingénieurs Électriciens sortis de L'Institut Électrotechnique Montefiore, 31 Rue Saint Gilles, Liège.

The Benevolent Fund.

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THEORETICAL AND EXPERIMENTAL STUDY OF THE ELECTRIC FIELD IN AN ELECTROLYTIC CELL.*

By ABDEL AZIZ AHMED, Ph.D., M.Sc.(Eng.), Associate Member.

(*Paper first received 11th September, and in final form 7th November, 1923.*)

SUMMARY.

The paper has for its principal object the theoretical and experimental investigation of the electric field produced when a current flows in an electrolytic cell having plane parallel electrodes.

On the theoretical side a general expression for the electrolytic conductance is derived in terms of the stream flux and the potential difference between the electrodes, and is applied to special problems of complex transformations. The distribution of the electric stress along the surface of parallel plane electrodes is also determined mathematically (see Section 1).

The experimental work has been planned with two objects in view: (1) To verify the theoretical results by means of experiments in which the mathematical conditions are represented with sufficient and reasonable accuracy (see Sections 2 and 3); and (2) to apply the theoretical results for the solution of certain practical questions, and to investigate experimentally how far such applications agree with test results (see Section 4). Both objects have been in some measure satisfactorily attained.

On the side of electro-physics the validity of Ohm's law is proved for any elemental current in the electrolyte by a direct experiment devised for this purpose (see Section 3). The significance of this result lies first in its providing tangible evidence of the coincidence of stream lines with lines of force everywhere in the electrolytic medium, and secondly, in its proving that under certain conditions an electrolyte may be taken to represent a perfect homogeneous dielectric with something approaching mathematical precision. As an example of the practical application of this theorem, a method is derived for calculating the conductance of such apparatus as metal-refining and simple electro-deposition tanks, and certain types of liquid rheostats. A practical chart which is provided for this purpose may prove useful to the designers of such apparatus (see Section 4).

Furthermore, the results obtained may find a field of application in the measurement of electrical and magnetic phenomena where the distribution of energy is analogous to that shown to exist in the electrolytic cell, as, for example, the capacity of an irregular system of conductors or the reluctance of a magnetic circuit.

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1. MATHEMATICAL STUDY OF THE ELECTRIC FIELD IN AN ELECTROLYTIC CELL.

Consider an electrolyte* in which a steady flow of current is maintained by the application of a potential difference between two conducting electrodes immersed in it. Various points in the electrolyte will in general be at different potentials. There will be a system of equipotential surfaces which are intercepted orthogonally by tubes of flow, indicating by their orientation the direction of the current at any point in the electrolyte. The representation of current distribution is analogous to that of an electrostatic field, and in what follows we shall begin by assuming that the tubes of flow coincide with Faraday tubes in the electrostatic field which would be produced in an analogous dielectric medium.†

Experiment shows that Ohm's law applies to electrolytes as precisely as to metallic conductors. Consider an element of a tube of flow passing through a given point P in the electrolyte. Let its length be ds and its cross-section a. Let i be the current density at P, and k the conductivity of the electrolyte. Then if dV be the potential drop in the elemental tube we have

$$dV = \frac{1}{k} \times \frac{ds}{a} ia$$

or

$$\frac{dV}{ds} = \frac{i}{k} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where dV/ds is the potential gradient at P.

We shall now investigate more fully the analogy

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

* The present discussion deals in particular with an electrolytic medium, but the same method of reasoning holds good for any conducting medium.

† The question as to whether stream lines follow the lines of force or whether they may be deviated by electromagnetic action has received attention. The results show that there is no electromagnetic effect (see R. HEILBRUN, *Annalen der Physik*, 1904, vol. 15, p. 988). The magnetic effect of electrolytic current was investigated by S. SHELDON and G. M. DOWNING (*Physical Review*, 1898, vol. 7, p. 122), where it was shown that an electrolyte contained in a rubber spiral produced the same electromagnetic effect as a metallic conductor having the same number of ampere-turns.

between the electrostatic and the current fields in the electrolyte, and for simplicity we shall assume that:

(1) The electrolyte is of infinite dimensions and that current flows between two electrodes immersed therein.
(2) The electrolyte is homogeneous and has constant conductivity throughout.
(3) The flow of current is steady.

Let V_1 and V_2 be the potentials of the electrodes, so that their potential difference is $V_1 - V_2$. Suppose the electrolyte to be replaced by air, and let each electrode receive an equal and opposite charge until the potential difference becomes equal to that in the current problem. The potential of the electrodes, however, may or may not be equal to that in the current problem. Let E_1 and E_2 be the new potentials of the electrodes. We have

$$V_1 - V_2 = E_1 - E_2$$

Let $E = V + C$.

Then we get

$$\frac{dE}{dr} = \frac{dV}{dr} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where dr is the outward-drawn normal at a given point on the electrode surface.

From Equation (1) the current flowing in the direction dr per unit area of the electrode surface is given by

$$i = k\frac{dV}{dr}$$

and the total flow of current from the electrode is

$$I = k\iint\frac{dV}{dr}dS$$

where dS is an element of the surface of the electrode. From (2) we also have

$$I = k\iint\frac{dE}{dr}dS$$

If Q be the quantity of electricity on each electrode, in the electrostatic problem we have by Gauss's theorem

$$\iint\frac{dE}{dr}dS = 4\pi Q = \psi$$

where ψ is the total electrostatic or dielectric flux emanating from each electrode.

Hence $$I = k\psi$$

If V be the potential difference (equal to $V_1 - V_2$) and K the conductance of the electrolyte so that

$$I = KV$$

then K will be given by

$$K = k\frac{\psi}{V} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The expression ψ/V represents the surface integral of stream lines per unit potential difference, and may be called the "geometric conductance"* of the medium, i.e. the conductance corresponding to unit conductivity, and we shall denote it by K' so that

$$K' = \frac{\psi}{V} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Similarly to (3) the resistance will be given by

$$R = \rho\frac{V}{\psi}$$

where ρ is the resistivity, and the "geometric resistance" by

$$R' = \frac{V}{\psi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Equation (4) is of practical importance, as it enables us to express the conductance of an electrolyte as a function of the potential difference between the electrodes and the flux issuing from them. The conductance thus expressed will be measured in the same unit as k.

Steady Flow in Two Dimensions.

When tubes of flow are the same in all planes parallel to that of xy, and there is no current parallel to the axis of z, we may regard the flow of current as being two-dimensional and consider only the circumstances in the plane xy.

Considering now two plane parallel electrodes immersed in an electrolyte, we may regard the flow of current between them in a normal plane sufficiently remote from their upper and lower edges as being two-dimensional. Let ds be an element of tube, and i the current density along ds as before. Let u and v be the components of i along the axes x and y, and l and m the direction cosines of u and v.

We have
$$u = li$$
$$= lk\frac{dV}{ds} \text{ from Equation (1)}$$

Hence
$$u = k\frac{dV}{dx}$$

and similarly
$$v = k\frac{dV}{dy}$$

Now for a steady motion the equation of continuity is given by

$$\frac{du}{dx} + \frac{dv}{dy} = 0$$

By substituting in this equation the values of u and v obtained above, we get

$$\frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} = 0$$

which is Laplace's equation for the potential function in two dimensions. This equation is satisfied by a solution of the form

$$\psi + jV = \chi(x + jy) \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where $j = \sqrt{(-1)}$.

The relation between ψ and V can be found by

* The term "geometric conductance" is analogous to "geometric permeance" as used by Karapetoff (see "The Magnetic Circuit," chap. 5, p. 93).

differentiating Equation (6) with respect to x and y. Thus we get

$$\frac{d\psi}{dx} + j\frac{dV}{dx} = \chi'(x + jy)$$

$$\frac{d\psi}{dy} + j\frac{dV}{dy} = j\chi'(x + jy)$$

whence

$$j\frac{d\psi}{dx} - \frac{dV}{dx} = \frac{d\psi}{dy} + j\frac{dV}{dy}$$

or

$$\frac{d\psi}{dx} = \frac{dV}{dy}, \quad \text{and} \quad \frac{d\psi}{dy} = -\frac{dV}{dx}$$

Functions satisfying these relations are called conjugate functions.

It is evident that the families of curves given by $\psi =$ constant and $V =$ constant intersect orthogonally at every point. In other words the curves $\psi =$ constant are stream lines, while the curves $V =$ constant are the equipotentials.

If stream lines and equipotentials are drawn for a series of equal infinitesimal increments of V and ψ they will divide the plane into infinitesimal squares. For if dx be the distance between two consecutive stream lines, and dy that between two consecutive equipotential lines, the current may be expressed by $d\psi/dx$ or dV/dy. Hence if $d\psi = dV$ then $dy = dx$.

Consider now more fully Equation (6) and let us write

$$z = x + jy$$

and

$$w = \psi + jV$$

so that

$$w = \chi(z)$$

If we represent values of z in one Argand diagram and values of w in another, it can be shown that corresponding infinitesimal parts of the two diagrams are similar, and Equation (6) is therefore said to transform a diagram in the z plane "conformally" into the w plane. Such transformations have been successfully applied for the solution of certain physical problems, especially in hydrodynamics and electricity, which are otherwise incapable of solution.

The condition that the potential over a conductor is constant may be represented in the w plane by straight lines parallel to the real axis, and since stream lines cut equipotentials orthogonally it follows that conductors in the z plane can be transformed conformally into rectangles in the w plane, provided the proper function χ in Equation (6) is found in each case. In other words, Equation (6) will transform an irregular conductor in the z plane into a rectangle in the w plane bound by straight lines $\psi =$ constant and $V =$ constant. These conductors will be electrically equivalent since the transformation is conformal, i.e. the mutual relationship between equipotentials and stream lines bounding corresponding infinitesimal parts is preserved in both conductors.

We shall now illustrate the use of the above method of transformation by simple examples.

Take the function

$$\psi + jV = (x + jy)^2$$
$$= x^2 - y^2 + 2jxy$$

so that $\psi = x^2 - y^2$; and $V = 2xy$.

The stream lines are rectangular hyperbolas with the axes of co-ordinates as axes, and the equipotential lines are also rectangular hyperbolas with the axes of co-ordinates as asymptotes. We can make use of this transformation to find the resistance of a conductor bounded by these lines, such as the shaded diagram in Fig. 1, where APB and A′QB′ are the stream-line boundaries, and AA′ and BB′ are the equipotential boundaries of the diagram in question.

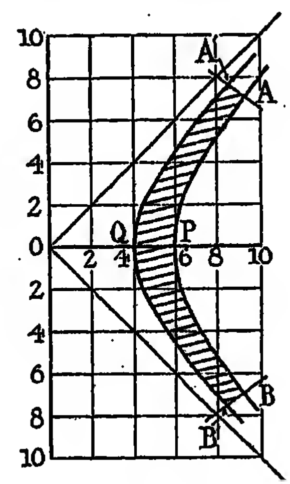


FIG. 1.

From Equation (5) the required resistance is given by

$$\frac{V}{\psi} = \frac{V_A - V_B}{\psi_P - \psi_Q} = \frac{2x_Ay_A - 2x_By_B}{(x_P^2 - y_P^2) - (x_Q^2 - y_Q^2)}$$
$$= \frac{2 \times 8 \times 8 - 2 \times 8 \times (-8)}{(6^2 - 0) - (4^2 - 0)} = 12 \cdot 8$$

Thus the irregular conductor APBB′QA′ is transformed into an equivalent rectangle whose boundaries are $V_A = 128$; $V_B = -128$; and $\psi_P = 36$, $\psi_Q = 16$.

Another simple example is given by the following transformation:

$$\psi + jV = \log(x + jy)$$
$$= \log re^{j\theta}$$

where r is the radius vector, and θ the argument in polar co-ordinates, or

$$\psi + jV = \log r + j\theta$$

Hence we have $\psi = \log r$, and $V = \theta$.

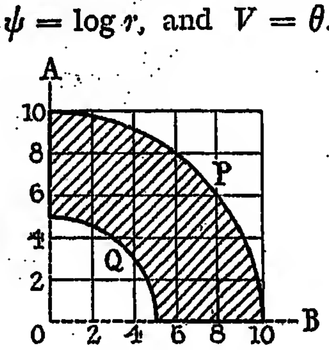


FIG. 2.

Thus the stream lines are a system of concentric circles, and the equipotentials radii diverging from their common centre. We can use this function to find the resistance of any figure bounded by these lines. Take as a special case the shaded portion of Fig. 2.

The equipotential boundaries are $V = 0$ and $V = \pi/2$, and the stream-line boundaries are $r = 10$ and $r = 5$. From Equation (5) the geometric resistance is given by

$$R' = \frac{V}{\psi} = \frac{V_A - V_B}{\psi_P - \psi_Q} = \frac{\frac{1}{2}\pi - 0}{\log r_P/r_Q} = \frac{\frac{1}{2}\pi}{\log (10/5)} = 2\cdot 27$$

The transformation illustrated by the above examples has been made directly from the z plane to the w plane. Such direct transformation, however, is not always possible, and in general it is effected through the intermediation of a third diagram, which is taken, for convenience, in the real axis of a semi-infinite plane.

If $t = \xi + j\eta$ represent a point in the semi-infinite plane, let

$$z = f(t) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and

$$w = F(t) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Equation (7) will transform a conductor in the z plane conformally into an equivalent diagram in the t plane, and Equation (8) will transform this again into the t plane.

The method of transformation discussed above has its limitations. The purely mathematical difficulties are such as to make it applicable only in a comparatively few simple cases.

The transformation of a rectangular polygon into the real axis of a half plane can be effected by means of a general theorem due to Christoffel and Schwarz, which states that

$$\frac{dz}{dt} = C(t - t_1)^{(\alpha_1/\pi)-1}(t - t_2)^{(\alpha_2/\pi)-1} \ldots (t - t_n)^{(\alpha_n/\pi)-1} \quad (9)$$

where α_1, α_2, α_n are the internal angles of the polygonal conductor in the z plane, and t_1, t_2, t_n are the co-ordinates of points in the t plane corresponding to the angular points of the polygon. Three of these co-ordinates are arbitrary and the rest are determined from the configuration of the polygon.*

We shall now proceed to apply this theorem for the solution of the problem with which we started, viz. the case of plane parallel electrodes immersed in an infinite electrolyte.

The plane equidistant and parallel to the electrodes is an equipotential and can be replaced by a conducting lamina without disturbing the configuration of equipotential and stream lines. The problem the solution of which is required can now be put in the following form, to which the Schwarzian transformation readily applies.

Imagine a semi-infinite plate CD (Fig. 3) at potential V placed at a distance h above and parallel to an infinite plate AB at zero potential; it is required to map out the distribution of electric stress or potential gradient at the electrode surface.

The polygonal conductor ABCDEA (traced by the dotted line) will first be transformed into an equivalent conductor having a straight-line boundary in the real axis of the t plane, and then transformed again by the same theorem into a rectangle in the w plane, bounded by equipotentials and straight lines. In order to transform the polygon to the t plane we assume three arbitrary values of t. Take $t = -\infty$ at the point A, $t = -1$ at the point (B, C) and $t = 0$ at D, then we shall have $t = \infty$ at E. The angles of this polygon are $\alpha = 0$ at (B, C) and $\alpha = 2\pi$ at D.

Hence we have by Schwarz's theorem

$$z = C\int \frac{t}{t-1} = C\,[t - \log (t + 1) + D] \quad . \quad . \quad (9)$$

where C and D are the constants of integration and may be determined from the boundary conditions of the plates. These, as assumed above, are at $y = 0$ and $y = h$. Hence we have

$$z = x + jy = \frac{h}{\pi}[t - \log (t + 1) + j\pi] \quad . \quad . \quad (10)$$

The diagram in the w plane consists of two parallel straight lines, KL and MN. The internal angle at (L, M)

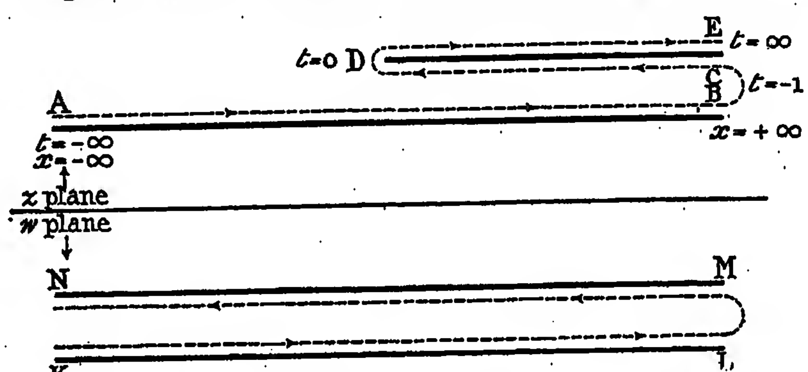


FIG. 3.—Diagram illustrating Schwarz's transformation.

corresponding to the point $t = -1$ is zero. This diagram is transformed to the t plane thus :—

$$\frac{dw}{dt} = A\frac{1}{t+1}$$

or

$$w = A \log t + B$$

A and B can be found from the condition that the two planes are, as previously assumed, at $V = 0$ and $V = V$; whence we have

$$w = \psi + jV = \frac{V}{\pi}(\log t - j\pi) \quad . \quad . \quad (11)$$

Equations (10) and (11) give the general solution of stream-line distribution for both plates.* Thus for the side DC we equate real quantities and obtain

$$x = \frac{h}{\pi}\{t - \log (t + 1)\} \quad . \quad . \quad . \quad . \quad (12)$$

and

$$\psi = \frac{V}{\pi}\log (t + 1) \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where t varies from 0 to -1.

Also from (12) and (13) we obtain the density of stream lines thus :—

$$\frac{d\psi}{dx} = \frac{d\psi}{dt} \times \frac{dt}{dx} = \frac{V}{h} \times \frac{1}{t}$$

* See J. J. THOMSON: "Recent Researches in Electricity and Magnetism," chap. 3; HORACE LAMB: "Hydrodynamics," chap. 4; and J. H. JEANS: "Electricity and Magnetism," p. 271; also J. F. H. DOUGLAS: "The Reluctance of Some Irregular Magnetic Fields," *Transactions of the American Institute of Electrical Engineers*, 1915, vol. 34, p. 1067, which contains useful references to original papers.

* Equations (10) and (11) are identical with those given by Sir J. J. Thomson in "Recent Researches," *loc. cit.*, to which the reader is referred for further explanation of the method of solution.

and from the conjugate property of ψ and V we get the electric stress

$$\frac{dV}{dy} = \frac{d\psi}{dx} = \frac{V}{h} \times \frac{1}{t} \quad . \quad . \quad . \quad . \quad . \quad (14)$$

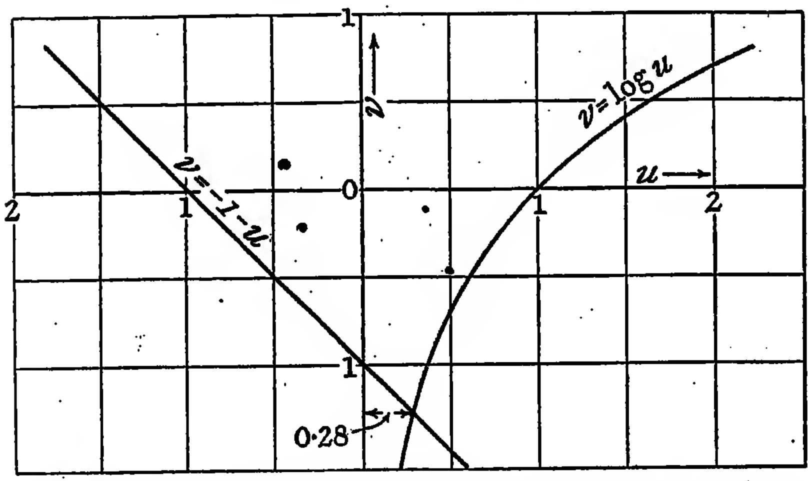


FIG. 4.—Graphical solution for determining t on the lower plate, corresponding to the extremity of the upper plate.

Similar expressions can be obtained for the side AB by putting $y = 0$ in (10) and (11); thus we get

$$x = \frac{h}{\pi}\{t - \log(-1 - t)\} \quad . \quad . \quad . \quad . \quad (15)$$

and

$$\psi = \frac{V}{\pi}\log(-1 - t) \quad . \quad . \quad . \quad . \quad (16)$$

Hence

$$\frac{d\psi}{dx} = \frac{dV}{dy} = \frac{V}{h} \times \frac{1}{t} \quad . \quad . \quad . \quad . \quad (17)$$

In this case t varies from -1 to $-\infty$.

Put $(-1 - t) = u$, and write the equation thus :—

$$\log u = -u - 1$$

This equation is best solved graphically by taking

$$v = \log u\,; \quad \text{and} \quad v = -u - 1$$

The corresponding graphs are shown in Fig. 4, where they intersect at the point $u = 0{\cdot}28$, which gives $t = -1{\cdot}28$.

Similarly we can find the point from which ψ is to be measured on the lower plate AB. We have from (16)

$$0 = \frac{V}{\pi}\log(-1 - t),$$

whence $t = -2$, which gives the corresponding value of x as $-0{\cdot}637$.

Thus for the lower plate AB, x is to be measured from the point $t = -1{\cdot}28$, and ψ from the point $t = -2$.

Fig. 5 shows the relative distribution of potential gradient on one electrode and the neutral plane, being calculated for an electrode 10 cm wide placed at a distance 10 cm from another identical electrode. The curves shown in this figure give also to a certain scale the current density near the electrode surface in a current problem, and to another scale the charge density in an electrostatic problem.

2. Experimental Work.

(A) *General plan.*—The experimental work has been planned with two objects in view: (1) To verify the mathematical results obtained in Section 1 on the distribution of electric stress near the electrode surface,

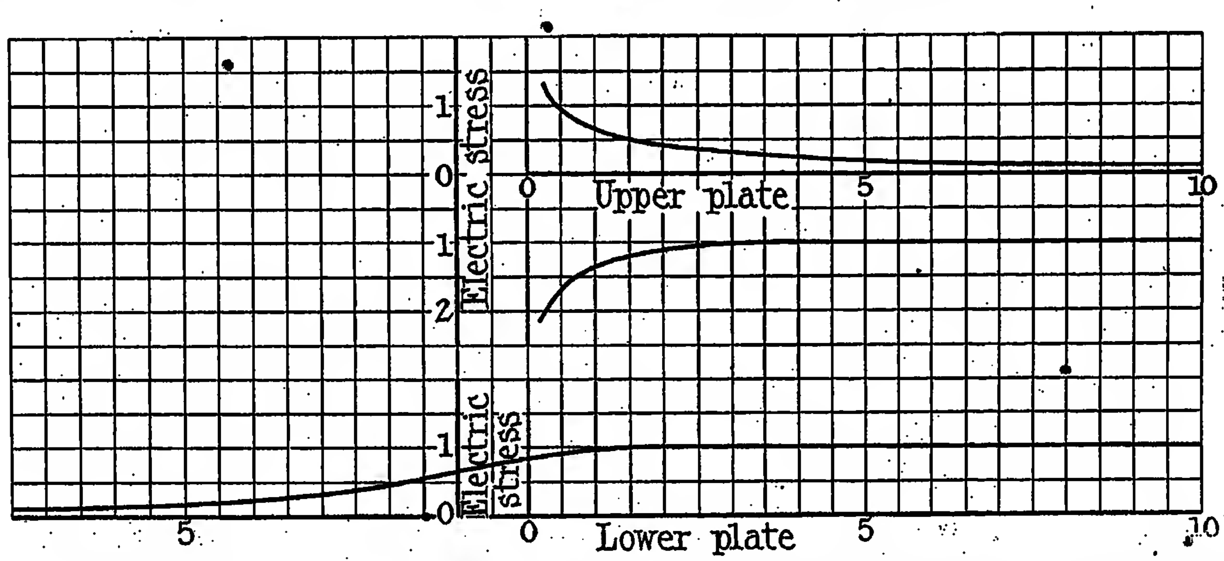


FIG. 5.—Relative distribution of electric stress on the upper and lower plates shown in Fig. 3.

Now for the side CD both x and ψ are to be measured from the point D, where $t = 0$ and $x = 0$. For convenience we shall measure x on the lower plate AB from the foot of the perpendicular let fall from D on AB, and in order to find the corresponding value of t we have, from (15),

$$0 = \frac{h}{\pi}[t - \log(-1 - t)]$$

or

$$t = \log(-1 - t)$$

by means of experiments in which the mathematical conditions are represented with sufficient and reasonable accuracy, and (2) to apply these results for the solution of certain practical questions, or rather to find out problems to which these results are applicable, and to investigate experimentally how far such applications agree with test results.

The principle which has been previously stated, viz. that tubes of flow are identical with tubes of force, enables us to replace a dielectric medium by a conducting

medium, and for this purpose an electrolytic cell is admirably suited.

The conjugate character of stream lines and equipotentials suggests the possibility of transposing the roles of equipotentials and stream lines, so that the electric field can be completely determined by mapping out either system. It appears, however, that experimental investigation on these lines has been confined to the tracing of equipotentials, and thus only a qualitative representation of the manner in which the electric stresses are distributed in a given field has been obtained.* In the experimental work to be described, measurement of potential gradient and also, in some tests, of elemental current have been taken in chosen planes of observation. These measurements also represent to another scale the electric stresses in an analogous electrostatic field, and in this manner the stress distribution is determined quantitatively as well as qualitatively.

(B) *Account of apparatus and method.*—The apparatus consists of two rectangular plane copper plates immersed in a solution of copper sulphate and contained in a large glass vessel (Fig. 6). The suspension of the electrodes is arranged on ball bearings operating in an oil bath so as to ensure that the electrodes are vertical as well as rigid. Each electrode with its suspension system can travel so as to give within the limits of the apparatus any required spacing between them. The spacing is measured on two scales fixed on either side of the vessel. The potential gradient at any point in the electrolyte is measured by means of two thin copper wires, insulated throughout with wax except near their extremities, thus acting as exploring points leading to a quadrant electrometer* as shown in Fig. 7. The exploring electrodes are held firmly in an ebonite block fastened to a glass tube in which the electrometer leads are housed. This tube is securely held in a sliding carrier capable of movement along a transverse scale,

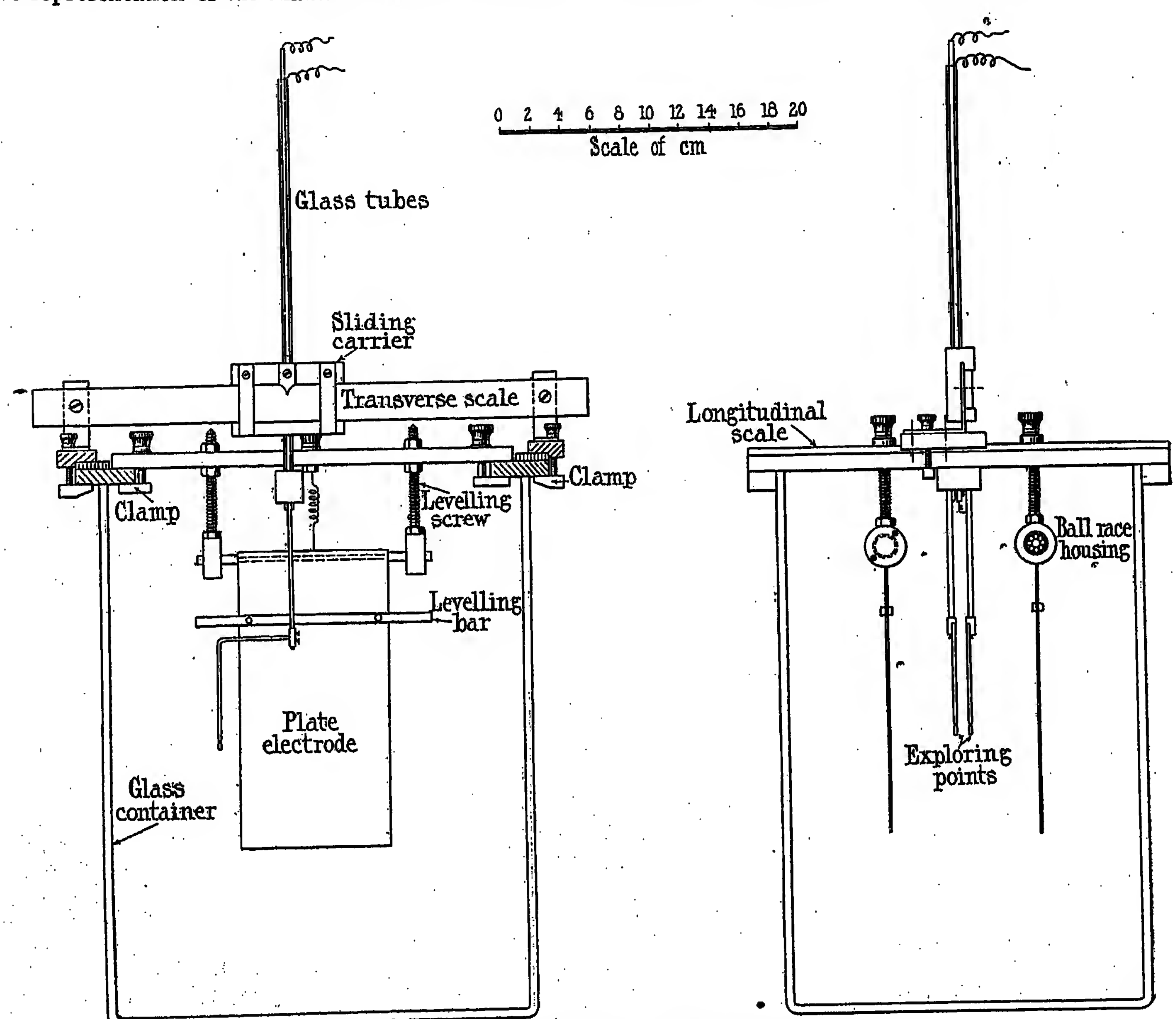


FIG. 6.—Diagram of apparatus for use with electrolytic cell.

* Such investigation has recently been carried out by C. L. FORTESCUE and S. W. FARNWORTH, *Transactions of the American Institute of Electrical Engineers*, 1913, vol. 32, pt. 1, p. 895.

* The electrometer is of the Dolezalek type, the needle being charged to 120 volts.

which in turn can travel with the sliding carrier along the two longitudinal scales fixed at the side of the vessel. In this manner the exact position of the exploring points can be read in rectangular co-ordinates.

In order to represent the mathematical conditions with sufficient accuracy, care has been taken to set the electrodes exactly symmetrical with each other, with reference to the neutral plane in which the exploring points have been previously adjusted to travel, so that each electrode coincides with the reflection of the other. For this purpose levelling bars are fixed to the electrodes above the water-level, at precisely the same distance from their lower edges and projecting sideways, so as to act as supports for a spirit-level and in general to act as a datum line from which all measurements are to be taken.

In order to secure the correct alignment the bearing housings are held by means of adjustable screws, which enable the movement of the electrodes to be effected in a vertical plane, while their motion in a horizontal direction is attained by sliding the bearings in their

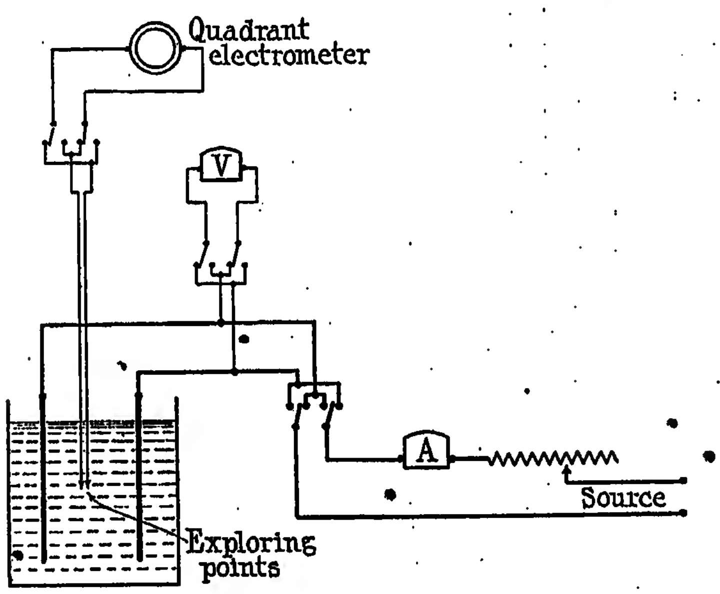


FIG. 7.—Diagram of connections.

housings. The spacing in the various tests could thus be adjusted to the nearest 0·25 mm.

(C) *Choice of elements of electrolytic cell.*—It is well known that when current from an external source is circulated through an electrolytic cell a counter E.M.F. is set up in the cell, which tends to diminish the current and is generally known as the polarization E.M.F. Principally it is the decomposition voltage which is responsible for the chemical work done in the cell. It is a physical constant for any particular cell, being independent of the magnitude of the current and varying according to the elements which compose the cell. Any increase in the rate of decomposition comes only from the current component of the power. It may therefore be deduced that in electrolytic cells where the flow of current does not produce definite chemical changes there would be no potential drop of decomposition. This is practically the case in electro-deposition cells, or in general in any cell where the electrodes are so chosen that the electrolyte is exactly reconstituted by the use of a soluble anode of the same nature as the cations which are being deposited; the sum total of the mass of metal remains the same, and the electrolyte undergoes practically no change. The chemical energy consumed in tearing the particles of deposit from the anode is recovered when these articles enter into chemical combination with the cathode, so that the algebraic sum of the energy consumed is zero and theoretically no work is done in the process of deposition.

In the cell described above, the electrodes were therefore chosen of pure copper and the electrolyte of a solution of copper sulphate.

In an electrolytic cell there is usually a certain quantity of gas evolved by electrolysis and adhering to one or both electrodes. The quantity of gas thus formed varies according to the material of the electrodes and is generally greater with inactive electrodes than with soluble ones.* The presence of gas bubbles has the effect of mechanically interrupting the flow of current at the points of the electrode surface to which they adhere, thus causing a diminution of the effective surface of the electrode and, consequently, local increase of current density. Now when current flows from one conductor to another there is generally some perceptible evidence of potential drop occurring at the surface of contact. In solids, contact is more or less perfect according to the nature and the state of the surfaces of contact, and for mechancial reasons an absolutely perfect contact is practically impossible. When a conductor is immersed in a liquid the conditions are more favourable for obtaining good contact, but as electrolysis begins the gas liberated increases the contact resistance. The potential drop due to contact resistance increases with current density, and hence it is evident that the effect of the gas bubbles would be to increase the potential drop at the surface of contact by increasing the current density. The author has carried out extensive tests for the purpose of ascertaining the magnitude of the potential drop occurring at the electrode surface in the particular cell described. These have been omitted from the paper for want of space, and only the results are given below:—

(*a*) No polarization E.M.F. could be detected in the cell.

(*b*) The contact resistance is from 4 to 6 per cent of the cell resistance, and varies with the current and the nature of the electrode surface, being greater with smooth than with rough surfaces. This may be due to the fact that a spongy surface which has been roughened by deposition presents a larger surface per unit area of electrode.

(D) *General comparison of the electrostatic and current problems.*—In the mathematical treatment the electrolyte is assumed to be homogeneous, and the potential difference maintained at the conducting plates is therefore a continuous function of the distance separating them. Neither of these conditions is strictly true for an electrolytic medium. In the first place, local changes of density occur in the neighbourhood of the electrodes, the electrolyte near the cathode becoming denser, and that near the anode weaker than the

* See LE BLANC: "A Text-book of Electro-Chemistry," p. 296.

rest, which practically maintains its original density. Secondly, there is generally an abrupt drop of potential at the surface of contact between the electrolyte and either electrode, which forms a discontinuity in the potential function. If the P.D. between one electrode and a point close to its surface be measured by an electrometer, the reading will give the fall of potential due to the resistance of the electrolyte which fills the space separating the point from the electrode surface, plus the P.D. occurring at the surface of contact.

It is evident, therefore, that the neighbourhood of the electrodes does not provide a suitable position for the verification of the mathematical expressions, and in order to attain this object with reliable and accurate results it is necessary to take measurements of potential gradient at a distance from material objects which are likely to disturb the homogeneity of the electrolyte and either side, and therefore may be regarded as being equivalent to the shifting of the boundaries of the electrolytic medium from the metal conductors to the adjacent equipotential surfaces, which may, as a first approximation, be assumed to be planes parallel to the electrodes. This corresponds to a reduction of spacing of the electrodes by an insignificant amount equal to the thickness of the gas film formed at the electrodes.

Incidentally there is another point which is uniquely possessed by the neutral plane as a suitable field for observation. Small lengths of tubes of flow in this region such as are intercepted by the exploring points are practically straight lines normal to the neutral plane. Thus when the transverse scale is adjusted so that the exploring points travel astride the neutral plane, readings of potential gradient can be taken for any point in the plane without altering either the setting of the transverse scale or

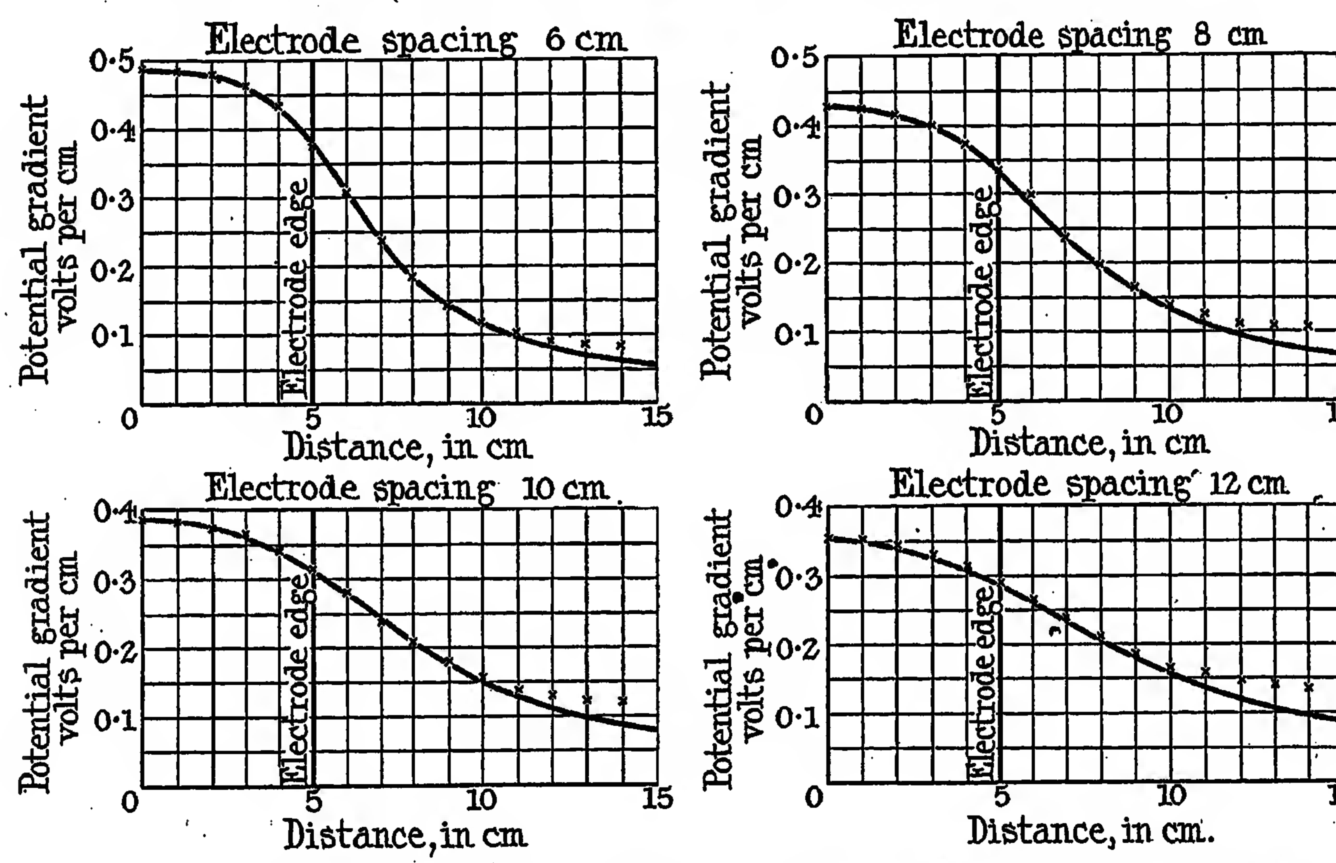


FIG. 8.—Comparison of theoretical and experimental results. Main current = 2 amperes.

introduce other uncertain factors. In this respect the neutral plane, i.e. the plane equidistant between, and parallel to, the electrodes, appears to be a suitable field of observation. It provides a hypothetical conductor which may be taken to represent the infinite plate in the mathematical problem (Fig. 3), while either electrode may be taken as the semi-infinite plate.

We shall now proceed to show that neither the local changes of density nor the contact drop at the electrode surface will materially affect the relative measurements of potential gradient in the neutral plane. For since the change of density is equal and opposite at the two electrodes, and therefore extends over the same distance from each electrode, it follows that in a space diagram the position of the neutral plane remains unchanged. The effect of the potential drop occurring at the surface of each electrode will be simply to reduce the applied pressure by an equal amount at the orientation of the exploring points. In any other plane or equipotential, however, the exploring points would have to be turned through an angle for each different reading so as to lie tangentially to the tube of flow passing through any particular point. This position can be found by trial, and corresponds to a maximum deflection of the electrometer for any given point in the electrolyte. The choice of the neutral plane for observation is amply justified by the general consistence of the numerous results obtained. Practically all the tests made in this plane show remarkable agreement between calculated and observed values of potential gradient. A few typical tests are given below.

(E) *Experimental results.*—In the following tests measurements of potential gradient have been taken at various points 1 cm apart along the neutral plane. The range of readings extended from the central line of the electrodes to the boundary of the glass container,

this operation being repeated for different electrode spacings.

Test 1.—The current was kept constant at 2 amperes for the various spacings 12, 10, 8 and 6 cm. The results are shown in Fig. 8, where the full-line curve gives the theoretical distribution of potential gradient, and the crosses are actual readings.

are shown in Fig. 10, the spacing being 10 cm. It will be shown in Section 3 that current density is proportional to potential gradient, so that Fig. 10 also represents the relative distribution of current on the front and back sides of the electrode.

(F) *Discussion of results.*—Examination of Figs. 8 and 9 shows, in general, good agreement between

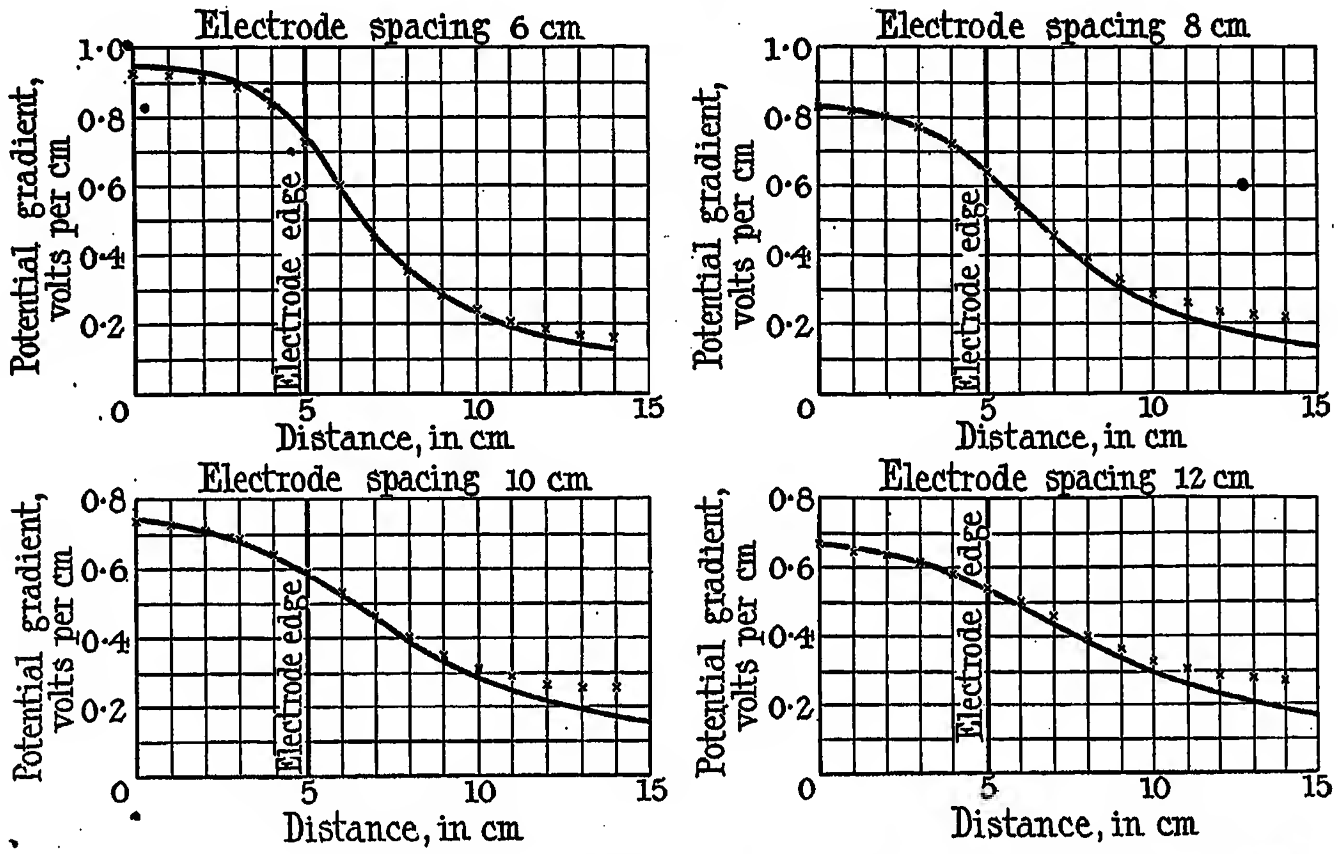


FIG. 9.—Comparison of theoretical and experimental results. Main current = 4 amperes.

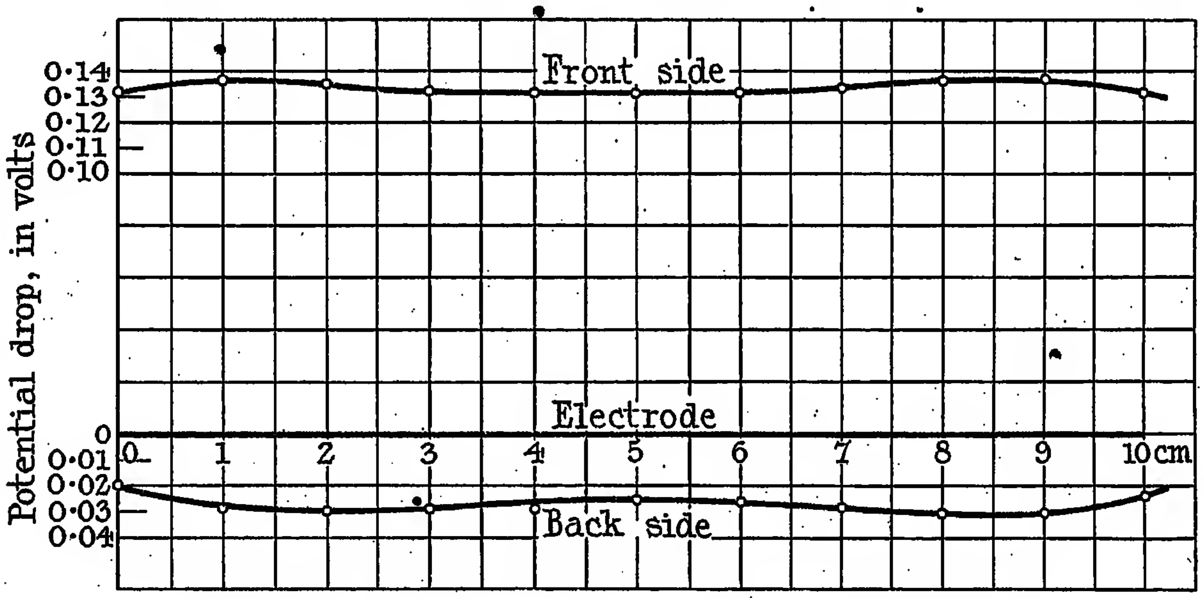


FIG. 10.—Potential-drop near front and back sides of electrode.

Test 2.—Is similar to Test 1 with the exception that the current was kept constant at 4 amperes. The corresponding curves are shown in Fig. 9.

Test 3.—In this test, readings of potential gradient were taken at a distance 1·5 cm from the electrode so as to eliminate local disturbances taking place in the proximity of the electrode. The object of this test was to give a picture of the relative distribution of potential gradient near the electrode surfaces, and the results

calculated and observed values of potential gradient in the neutral plane, except at the lower parts of the curves, i.e. near the boundary of the glass container, where the experimental values are slightly higher than those obtained by calculation. This is common to all the curves, and is principally due to the restrictive influence of the non-conducting boundary on the direction and density of stream lines in that neighbourhood. It will be remembered that in the mathematical

treatment of the problem the medium was assumed to be of infinite dimensions, so as to eliminate the restrictive effect of the boundary on the free flow of stream lines in order to simplify the problem. The same condition would be fulfilled if the fixed boundaries of the conducting medium were so shaped as to follow in each case the direction of a given stream line. In such a case there would be no component of current normal to the boundary, as is evident from the definition of a

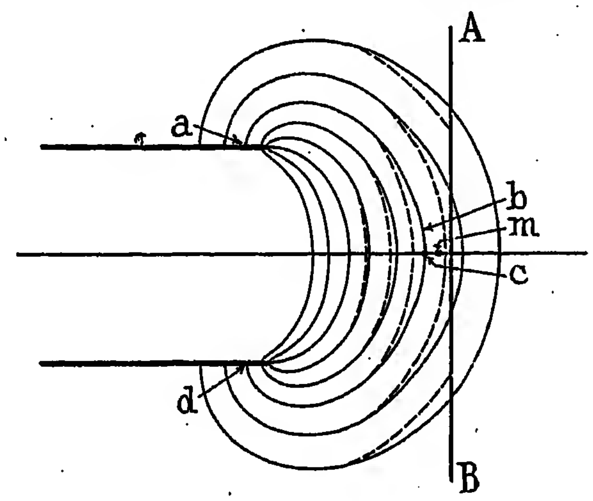


FIG. 11.

stream line. If the position of the boundary does not follow a stream line there would be always a restricted flow of current normal to its surface, and this would create a local disturbance. This is actually the case in the present experiments.

Suppose that the field of stream lines is already established between two electrodes immersed in an electrolyte of infinite dimensions. Let now a boundary surface approach the field, coming from a distance until it occupies the position AB in Fig. 11. Let abcd

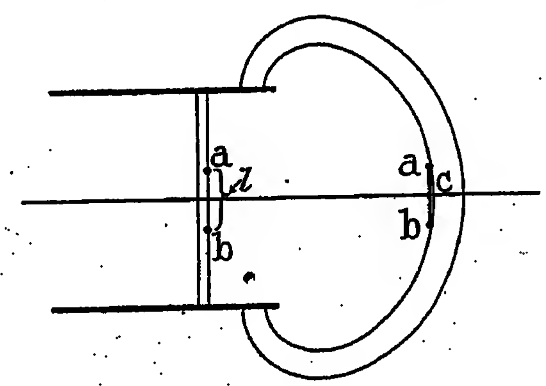


FIG. 12.

represent a stream line and assume first that its position remains the same as before the insertion of the boundary surface. The stream lines to the left of abcd will obviously remain as before in their original respective positions. Those to the right of abcd, impinging on the non-conducting boundary surface and thus being diverted from their natural course, will concentrate in the space enclosed between that boundary and the stream line, abcd, giving rise to increased current density. The potential gradient, say, at a point m in that narrow space will therefore rise to correspond and would assume a higher value than that at c. Since, however, the fall of potential must take place in a progressive manner from the electrodes outwards, it follows that the line abcd must readjust itself by moving to the left in order to occupy such a position that c will have a higher potential gradient than m. Adjacent stream lines will rearrange themselves in a similar manner and follow the dotted lines shown in Fig. 11, with the result that the potential gradient of points near the boundary become higher than their corresponding values if there were no boundary, i.e. higher than the values obtained mathematically.

This explanation accounts for the rise of observed values of potential gradient at the lowest parts of the curves of potential gradient, i.e. in the proximity of the boundary. It will be noticed, however, particularly in the curves taken for large spacing, that the deviation of observed from calculated values starts soon after leaving the inter-electrodal space, indicating that the boundary is not solely responsible for the rise of observed readings over the calculated values.

Let a and b be the exploring points, and l the distance between them (Fig. 12). In the inter-electrodal space stream lines run more or less normally to the neutral plane, and so the line ab, having been previously adjusted perpendicular to the neutral plane, coincides more or less closely with the direction of stream lines, the smaller the spacing the better the normality of stream lines and the closer the coincidence of the line ab with the stream line passing through any particular point.

If V be the P.D. measured across the exploring points, then the potential gradient dV/dl will be given approximately by V/l. Outside the space enclosed between the electrodes, however, stream lines begin to assume curved shapes, so that ab will now bridge an arc acb, which may be appreciably greater than l. If s be the length of the intercepted arc then the approximate potential gradient should be given by V/s and not by V/l. Thus the observed reading of potential gradient may be higher than the true value as calculated mathematically, the discrepancy being greater the more curved are the stream lines, i.e. the wider the electrode spacings.

3. A METHOD OF MEASURING THE CURRENT DENSITY AT ANY POINT IN THE INTERIOR OF AN ELECTROLYTIC MEDIUM.

The principle of the method lies in circulating current from an external source between the exploring electrodes while lying in a given position inside the electrolyte, through which current is already flowing between the main electrodes. The direction of the exploring electrodes is such that the line joining them follows the path of stream lines in the given position. The current impressed on the exploring points is of opposite direction to that of the main current in the electrolyte, and of such a magnitude as to reduce the potential difference of the exploring points to zero. The diagram of connections is given in Fig. 13. When this condition is fulfilled the impressed current exactly neutralizes the main current localized at that particular position where the exploring points are inserted. This is shown when a galvanometer connected across the exploring points gives no deflection. The balancing current (indicated on a milliammeter placed in the

circuit of the independent source) is a measure of the current density at that particular point.

The potential gradient may be read on the electrometer before the impressed current is switched on, and so the relation between the potential gradient and the current flowing in any position of the exploring points may be determined.

Theory of the method.—Consider first the case when the main current through the cell is interrupted, and that

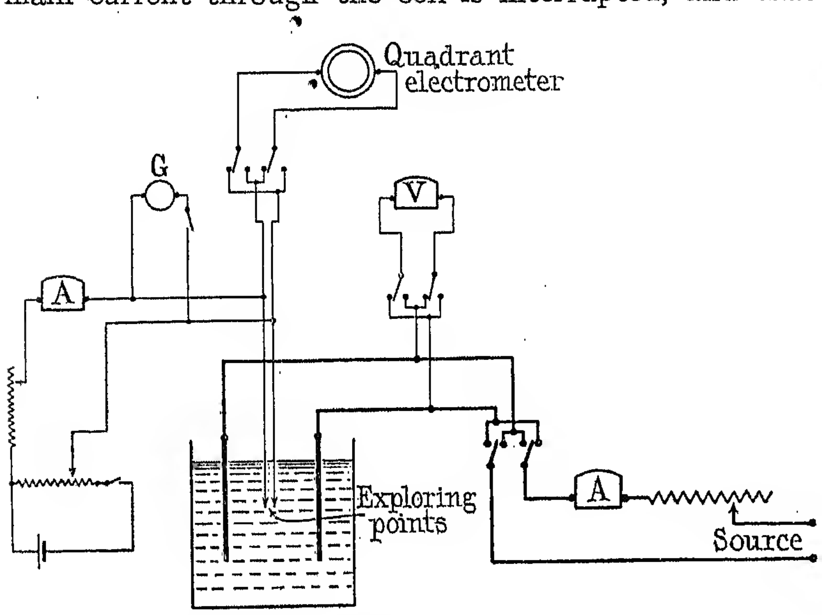


FIG. 13.—Diagram of connections.

only a current I supplied by the external source is impressed on the exploring points while lying in a given position in the electrolyte. We shall now proceed to find the resistance between these electrodes.

Take the transformation

$$w = \log \frac{z - c}{z + c}$$

where w and z have the same significance as before, so that we have

$$V + j\psi = \log \frac{x + jy - c}{x + jy + c}$$

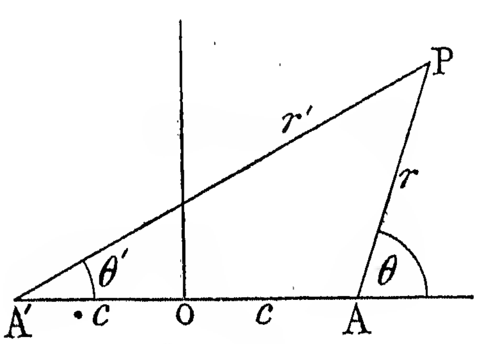


FIG. 14.

In Fig. 14 let OA = OA′ = c, and let P be a point $x + jy$.

It is clear from the figure that (vectorially)

$$\text{AP} = x - c + jy$$

and $$\text{A'P} = x + c + jy$$

Let $$x + jy - c = r\epsilon^{j\theta}$$

and $$x + jy + c = r'\epsilon^{j\theta'}$$

We obtain

$$V + j\psi = \log \frac{r\epsilon^{j\theta}}{r'\epsilon^{j\theta'}} = \log \frac{r}{r'} + j(\theta - \theta')$$

so that $$V = \log \frac{r}{r'}; \quad \text{and} \quad \psi = \theta - \theta'$$

It is obvious that the stream lines are circles passing through A and A′, and the equipotentials are an orthogonal family of circles. The solution therefore represents flow from a fictitious " source " placed at A to an equal negative source or " sink " placed at A′ (see Fig. 15).

Applying these functions to find the resistance between two cylindrical electrodes immersed in an electrolyte, we may regard one electrode as a " source " of current and the other as a " sink."

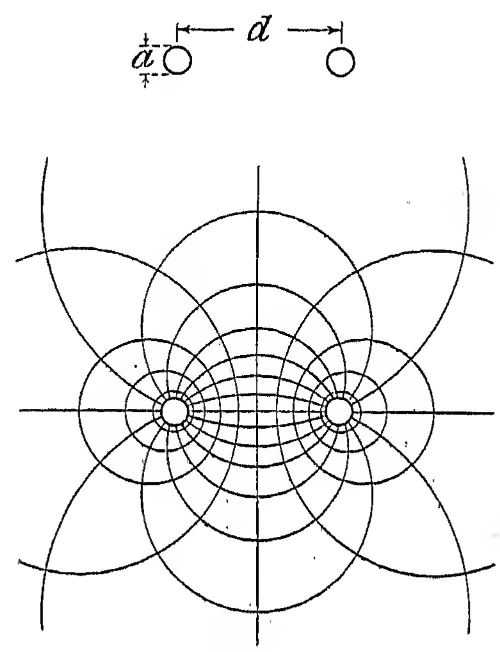


FIG. 15.

Let a be the radius of each electrode, and d the distance between their centres, assumed to be great compared with a. The equipotential boundaries of the medium the resistance of which is required are the traces of the electrodes, and its stream-line boundaries are given by $(\theta - \theta') = 0$ and $(\theta - \theta') = 2\pi$.

The two-dimensional geometric resistance can be found by applying Equation (5) thus:—

$$R' = \frac{V}{\psi} = \frac{\log (r/r')}{\theta - \theta'}$$

where r varies from $r = a$ to $r = (d - a)$, and r' from $r' = (d - a)$ to $r' = a$; while $(\theta - \theta')$ varies from $(\theta - \theta') = 0$ to $(\theta - \theta') = 2\pi$. Hence we have

$$R' = \frac{V - V'}{\psi - \psi'} = \left\{ \Big[\log r\Big]_a^{d-a} - \Big[\log r'\Big]_{d-a}^{a} \right\} \times \left[\frac{1}{\theta - \theta'}\right]_0^{2\pi}$$

$$= \frac{1}{2\pi} \log \frac{(d-a)^2}{a^2} = \frac{1}{\pi} \log \frac{d-a}{a} \qquad (18)$$

This equation gives the geometric resistance between the exploring electrodes in two dimensions, i.e. the resistance between their traces in a plane perpendicular to their length. If l be the depth of the uninsulated

part of either electrode,* their resistance will be given [from Equation (18)] by

$$R' = \frac{1}{l\pi} \log \frac{d-a}{a} \quad . \quad . \quad . \quad . \quad (19)$$

Let now a current be sent through the cell of such a value as to produce a current density i in the position occupied by the exploring points, and of opposite direction to the impressed current I. Since the line joining the exploring points follows the stream-line direction, i may be taken as being constant along that line. Hence the potential difference between the equipotentials passing through the exploring points due to a current density i is obviously $i\rho d$, where ρ is the resistivity of the electrolyte and d, as before, the distance between the exploring points. Let the impressed current I be so adjusted that the potential difference between the exploring electrode is zero. Hence we have

$$i\rho d = I\rho R'$$

whence

$$i = \frac{R'}{d} I = cI$$

This equation gives the current density i in terms of the balancing current I, which is read on the milliammeter, c being the constant of proportionality given by

$$c = \frac{R'}{d} = \frac{1}{dl\pi} \log \frac{d-a}{a}$$

In the following experiment various readings of elemental current were taken in the neutral plane by the method just described, while the main current through the cell was kept constant at 2 amperes; corresponding readings of potential gradient were also taken on the electrometer. The results are shown in Fig. 16. The effective resistance between the exploring points has been calculated from the ratio of corresponding ordinates of both the potential gradient and current curves. The resistance graph is shown to be a straight line parallel to the x axis, i.e. the resistance is constant.

This result proves the validity of Ohm's law for any elemental current in the electrolyte. Furthermore, it shows that the potential gradient at any point can be replaced by the current. The latter result is instructive, as it provides an experimental proof of the conjugate property of stream and equipotential lines, so that we have

$$i = \frac{dI}{dx} = \frac{1}{\rho} \times \frac{dV}{dy} = \frac{1}{\rho} \times \frac{d\psi}{dx}$$

or

$$I = \frac{\psi}{\rho} = k\psi$$

which is identical with the expression given on page 302.

We can now calculate the geometric resistance between the exploring electrodes by applying Equation (19) and substituting the actual dimensions of these electrodes. Thus we have

$$R' = \frac{1}{l\pi} \log \frac{d-a}{a}$$

* The exploring electrodes used were insulated all over with paraffin wax with the exception of a length of 5 mm near their extremities which was left uninsulated. The extremities themselves were also wax-insulated so that the end effect was thereby eliminated.

In the present test the measured dimensions were:

$$d = 1 \text{ cm}$$
$$l = 0\cdot5 \text{ cm}$$
$$2a = 0\cdot2 \text{ cm}$$

Hence

$$R' = \frac{1}{0\cdot5\pi} \log 9 = 0\cdot637 \times 2\cdot197 = 1\cdot4$$

Now we have from the resistance graph (Fig. 16) $R = 70\cdot5$ ohms, hence the resistivity of the electrolyte can be deduced thus:—

$$\frac{R}{R'} = \frac{70\cdot5}{1\cdot4} = 50\cdot3 \text{ ohms/cm}^3$$

and the conductivity is therefore given by

$$k = 0\cdot0199 \text{ mho/cm}^3$$

Confirmation of results.—It is evident from the above discussion that the ordinate of the current curve shown in Fig. 16 when multiplied by c gives the current density in the neutral plane. Since the total current emanating from the front and back sides of the electrodes passes through the neutral plane, it follows that the line integral of the current density in this plane gives the current flowing in a horizontal slice of the electrolytic cell 1 cm deep. This can be obtained by taking the area of the current curve and multiplying it by c. The total current in the cell can then be calculated from the dimensions of the electrodes and the lateral and bottom margins as follows:—

Numerical calculations.—Electrode dimensions (immersed surface) = $13\cdot6 \times 10$ cm^2, and bottom margin = $11\cdot1$ cm. The current curve (Fig. 16) extends from the central line of the electrodes to the walls of the glass vessel, so that the lateral margin (which is the same on either side of the electrode) is included in the current curve. Hence the area of this curve multiplied by c gives half the current sheet flowing in a slice 1 cm deep taken horizontally through the cell.

The current area for the bottom margin can be estimated by producing the current curve (Fig. 16) to a point $11\cdot1$ cm from the electrode edge, which is the length of the bottom margin, and taking the corresponding area from this curve. Hence we have:—

Area of current curve (Fig. 16) from the electrode centre to the vessel wall	=	42·35 mA-cm
Current area for a horizontal slice 1 cm deep = 2 × 42·35	=	84·7 mA-cm
Current area per cm length of bottom margin	=	24·0 mA-cm
We therefore have		
Current volume in the inter-electrodal and lateral space = 84·7 × 13·6	=	1 150 mA-cm^2
Current volume in the bottom marginal space = 24·0 × 10	=	240 mA-cm^2
		1 390 mA-cm^2
	=	1·39 A-cm^2

Hence total current through the cell = $1\cdot39c = 1\cdot39 \times 1\cdot4$ = 1·95 amperes

Actually the current in the cell was kept constant in the above test at 2 amperes, so that the discrepancy is about 2·5 per cent. It will be noticed, however, that the centage of the total current and would probably account for the above discrepancy.

An important conclusion which may be drawn from

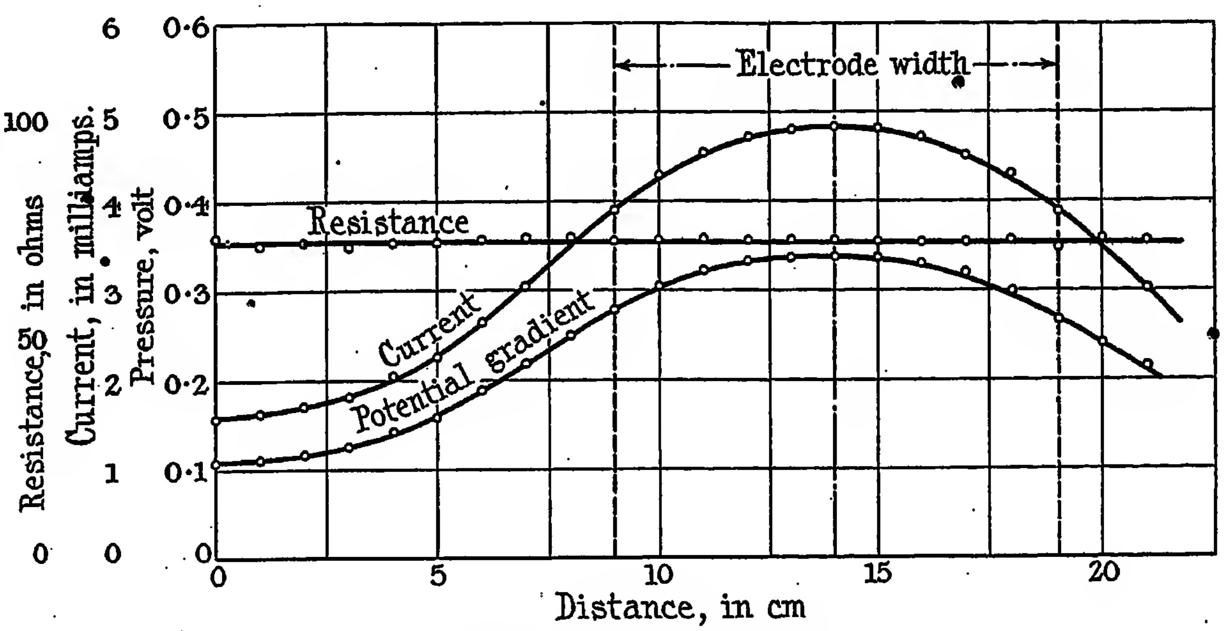


FIG. 16.—Distribution of potential gradient and current in the neutral plane.

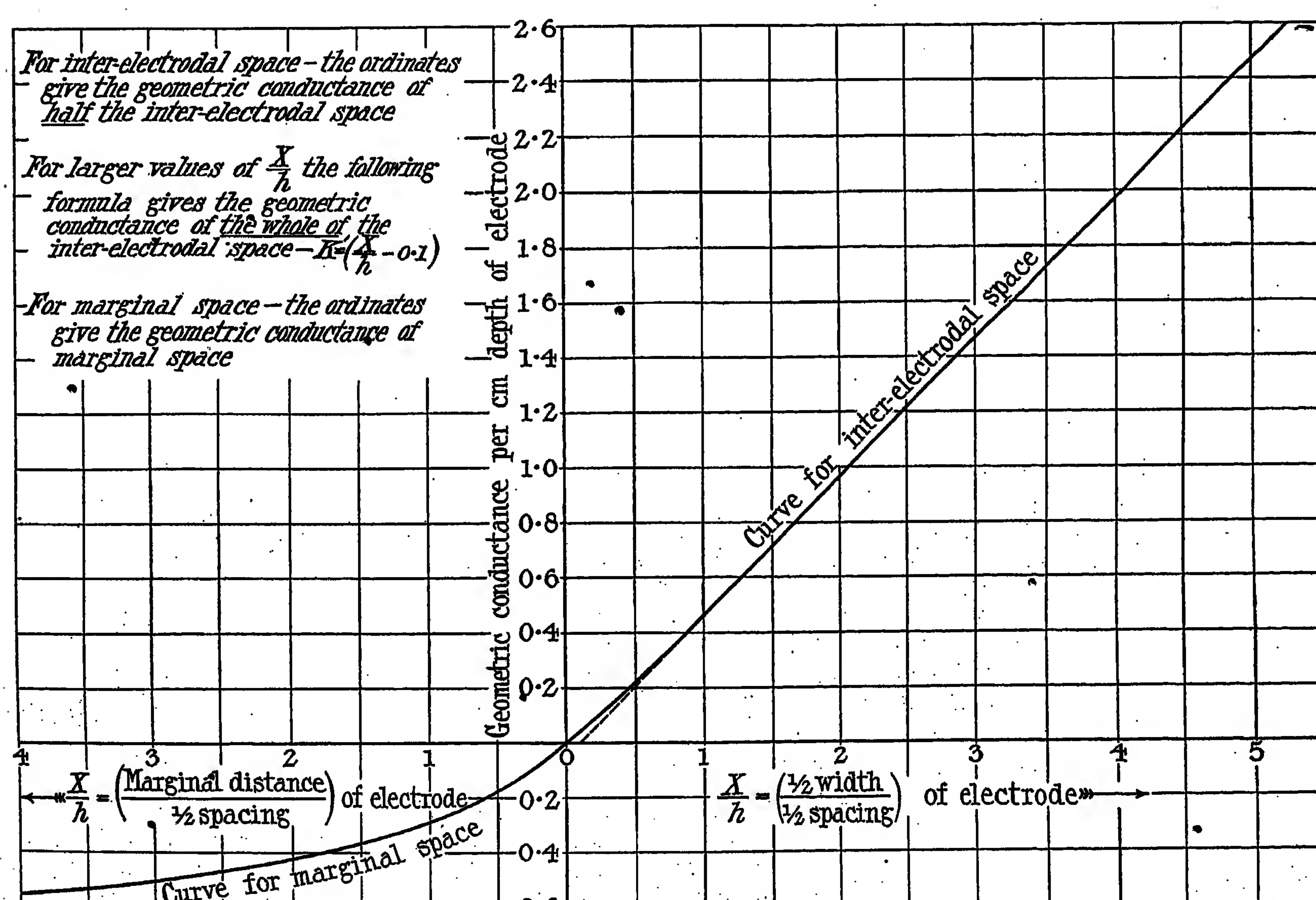


FIG. 17.—Chart for finding the geometric conductance of an electrolytic cell with plane parallel electrodes.

current issuing from the corner points of the electrodes is not taken into account in the above calculation, as the flow from these points is no longer two-dimensional. It is conceivable that this current is only a small per-

the above experimental results is that at any point in the electrolyte stream lines rigidly follow the direction of electric stress, so that an electrolyte may be taken to represent a perfect homogeneous medium with something

approaching mathematical precision. Thus a homogeneous dielectric such as air may be represented by an electrolyte in which the measurement of current would give to a certain scale the dielectric flux, which is otherwise impossible of measurement by direct experiment.

The importance of this result lies in its application to the practical measurement of such electric quantities as may be determinable by the measurement of the dielectric flux involved, e.g. the capacity of an irregular system of conductors. The method of procedure would be to take an electrolytic analogue of the dielectric circuit and measure its conductance, then to take another simple system whose capacity can be calculated mathematically (such as two parallel wires) and measure its conductance in the same electrolyte. The required capacity can then be found from the ratio of the two conductances and the known capacity of the two wires.

4. Calculation of the Geometric Conductance of an Electrolytic Cell having Plane Parallel Electrodes.

Consider first the case of two plane parallel electrodes such as those shown in Fig. 3. The geometric conductance in two dimensions is given by the line integral of the stream lines issuing from either electrode per unit potential difference, or by Equation (4)

$$K' = \frac{\psi}{V}$$

In order to evaluate ψ in this equation the simpler way is to take the stream flux on the lower plate AB in Fig. 3, as this represents the sum of stream lines emanating from the front and back sides of the upper plate CD. This flux is given by Equation (16), viz.

$$\psi = \frac{V}{\pi}\log(-1-t)$$

and hence
$$K' = \frac{\psi}{V} = \frac{1}{\pi}\log(-1-t) \quad . \quad . \quad . \quad (20)$$

Equation (20) thus enables us to find in the case under consideration the geometric conductance of the electrolyte between any assigned boundary values of t, where t varies from -1 to $-\infty$.

In order to express the dimensions on the electrolytic cell in terms of t we have from Equation (15)

$$\frac{x}{h} = \frac{1}{\pi}\{t - \log(-1-t)\} \quad . \quad . \quad . \quad . \quad (21)$$

Hence Equation (20) gives

$$K' = f(t) = f(x/h) \quad \text{[by Eqn. (21)]}$$

so that the geometric conductance for the above case can now be calculated by means of Equations (20) and (21).

We shall now proceed to deduce similar expressions for the geometric conductance between two parallel plane electrodes placed opposite to each other in an electrolytic cell.

Imagine a lamina placed in the neutral plane so as to divide the cell into two equal sections symmetrically situated about the neutral plane. Each section will then be analogous to the case considered above. The introduction of such a lamina does not affect the original distribution of current in the cell, as it coincides with an equipotential surface, viz. the neutral plane. Since the two halves into which the cell is thus divided are in series with each other, the resultant conductance is obviously half of each and is therefore given from Equation (20) by

$$K' = \frac{1}{2\pi}\log(-1-t) \quad . \quad . \quad . \quad . \quad (22)$$

Thus Equation (22) gives the geometric conductance of the cell in two dimensions, i.e. the geometric conductance of a slice of unit depth taken through the cell normal to the electrode planes.

Construction of a Chart for Finding the Geometric Conductance of an Electrolytic Cell with Plane Parallel Electrodes.

We can now construct a chart for finding the geometric conductance of an electrolytic cell or any portion

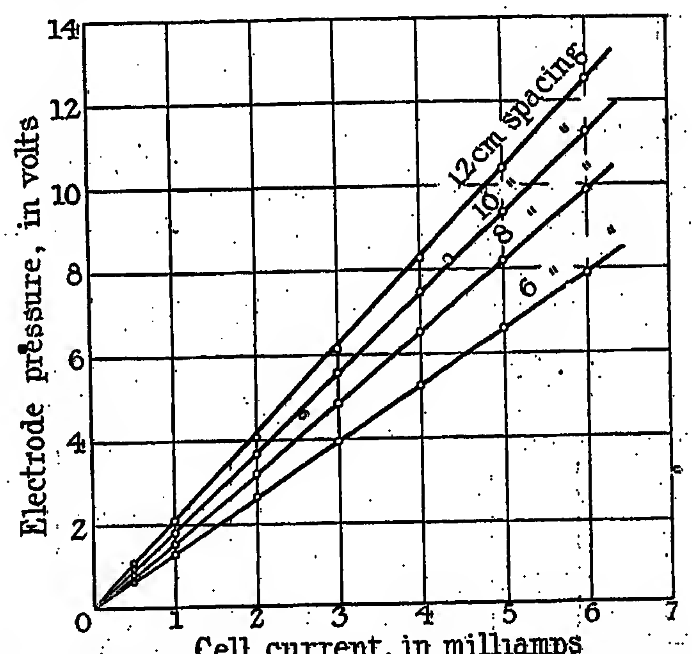


Fig. 18.—Measurement of the conductance of an electrolytic cell.

of the electrolytic circuit between two assigned limits, by taking various values of t in Equations (21) and (22). Such a chart, shown in Fig. 17, gives the geometric conductance in terms of x/h, where h is half the electrode spacing and x the distance measured from the electrode edge, and has the following significance:

(a) For the inter-electrodal space, x is to be taken equal to one-half the width of the electrode, and x/h is taken in the chart along the positive side of the x axis. The corresponding ordinate of the curve gives the geometric conductance of half the inter-electrodal space.

(b) For the lateral space or the marginal space beneath the electrodes, x is equal to the distance from the electrode edge to the boundary wall of the containing vessel, and x/h is taken in the chart on the negative side of the x axis. The corresponding ordinate of the curve gives

the geometric conductance of that portion of the cell to which x refers.

In order to illustrate the use of the chart we shall take the following simple example:

To find the geometric conductance per unit depth of an electrolytic cell having the following dimensions:—

Electrode width = 20 cm
Lateral margins = 6 cm each
Spacing = 10 cm

(*a*) *For the inter-electrodal space*

$$\frac{x}{h} = \frac{\frac{1}{2}\,(\text{Electrode width})}{\frac{1}{2}\,(\text{Electrode spacing})} = \frac{10}{5} = 2$$

From the chart (Fig. 17) the conductance K' of half the inter-electrodal space = 0·965

(*b*) *For one marginal space*

$$\frac{x}{h} = \frac{\text{Marginal distance}}{\frac{1}{2}\,(\text{Electrode spacing})} = \frac{6}{5} = 1\cdot 2$$

From the chart the conductance K' of marginal space .. .. .. = 0·315

Hence the geometric conductance of one-half of the cell per unit depth = 0·965 + 0·315 = 1·28

and the geometric conductance of the cell per unit depth is therefore .. = 2·56

It may be observed from Fig. 17 that for large values of x/h the geometric conductance curve is practically a straight line, which, when produced, cuts the x axis at the point $x/h = 0\cdot 1$. A formula can therefore be deduced which gives the geometric conductance for values of x/h beyond the range shown in the chart. Let α be the angle which the straight line part of the curve produced makes with the x axis. Then we have

$$K' = [(x/h) - 0\cdot 1] \tan \alpha$$

where $\tan \alpha = 0\cdot 5$ (approximately).*

Therefore $$K' = \frac{1}{2}[(x/h) - 0\cdot 1]$$

This formula gives the geometric conductance of half the inter-electrodal space, so that for the whole of that space we get

$$K' = (x/h) - 0\cdot 1$$

The same chart can be used for cases where the electrodes are of unequal dimensions, e.g. the case shown in Fig 3, discussed at the beginning of this section. Here h is to be taken as the total electrode spacing, and x will have the same significance as explained above. The geometric conductance, however, will be twice that given by the chart for any particular value of x/h.

The total geometric conductance of the cell (in three dimensions) can now be easily calculated from the electrode and marginal dimensions of the cell, as shown in the table.*

Confirmation of Results.

In the table on page 316 the geometric conductance of the electrolytic cell experimented with was calculated for different electrode spacings by the use of the chart (Fig. 17). The actual conductance of the cell was measured experimentally for the same spacings, and the results are shown in Fig. 18. The conductivity of the electrolyte was then deduced from the ratio of the measured conductance to the corresponding geometric conductance obtained by calculation. The average value works out as 0·0191 mho/cm^3.

In order to verify the results thus obtained the conductivity of the actual electrolyte was determined in a separate experiment arranged specially for the purpose. A description of the apparatus and the method used is given in Appendix 2. The value obtained for the conductivity was 0·02 mho/cm^3.

Conclusion.

Inspection of the previous table shows that the values of conductance calculated by the use of the chart (Fig. 17) are in fair agreement with those obtained experimentally.

The proportionality of geometric conductance to conductance is obvious from the table. The average conductivity obtained by calculation works out at 0·0191, against 0·02 obtained by direct experiment (see Appendix 2), with a difference of 4 per cent, which may be permissible in a calculation of this description. This result also compares favourably with the value of the conductivity obtained in Section 4, where its calculation by a different method gives 0·0199 mho/cm^3.

Some Practical Remarks.

Some interesting deductions may be made from the previous discussion, which may be of use to the designer of ordinary metal-refining tanks and liquid rheostats.

It will be observed from Fig. 17 that the value of the margin in contributing to the conductance of the cell per unit of its length decreases as we recede from the electrode edge. The most useful part of the margin in this respect appears to extend from the electrode edge to a point $x/h = 2$. Any increase of margin beyond this point adds comparatively little to the conductance of the cell. The rate of increase of conductance approaches zero as a limit.

It may be added that for a given size of electrode the relative contribution of the margin to the conductance increases with electrode spacing, and conversely. An economical limit can be determined by consideration of the relative size of tank and electrodes to give a specified conductance.

A practical illustration of the use of the above results is afforded where graphite or some similar expensive

* The ultimate value of $\tan \alpha$ is $\frac{1}{2}$ at a distance sufficiently remote from the edge so that the field becomes uniform. For if x be the width of a portion of the inter-electrodal space lying in such a uniform field, and $2h$ its length (electrode spacing), the geometric conductance, i.e. the conductance for unit conductivity, is $\frac{1}{2}\,x/h$.

* Electrochemists use the term "cell constant" to denote what we have called the "geometric conductance" of the cell. It is determined experimentally for any particular cell of given configuration by using an electrolyte of known conductivity and measuring the conductance of the cell by the well-known Kohlrauch or similar method whence the cell constant is deduced.

substance is employed as one of the electrodes. The question arises in this case as to how far a diminution of the electrode area can be compensated for by the lateral conductance of the electrolyte.

The results are probably equally important to the electrical engineer in the design of equalizing bars and heavy busbars of short length. They show the importance of making contact over the whole end of a heavy bar in order to utilize fully the metal of the bar.

In conclusion the author wishes to express his cordial thanks to Professor W. Cramp, D.Sc., for his helpful advice during the course of the present investigation as well as for reading the paper in manuscript. The whole of the work has been carried out at the University of Birmingham.

(3) The concentration of the electrolyte was kept constant throughout the various tests, and a constant level was maintained in the cell. The solution contained 100 grammes of copper-sulphate crystal per litre.

(4) It was noted that when the current was first switched on, the first set of readings were sometimes erratic and inconsistent with subsequent tests. It appears as though this was due to want of uniformity in the ionization of the electrolyte at the start. It was therefore arranged to allow about 15 minutes before taking any readings. It is significant that such an allowance was not necessary after a reversal of current, but only at the beginning of each working day.

(5) As a rule, when the current was kept constant in any particular test the P.D. across the electrodes also

Calculation of the Geometric Conductance of the Cell experimented with for Various Electrode Spacings.

Dimensional data:

- Electrode height (immersed) .. .. = 13·6 cm
- Electrode width .. .. = 10·0 cm
- Lateral margin .. .. = 9·0 cm
- Bottom margin .. .. = 11·1 cm

Electrode spacings: 12, 10, 8 and 6 cm.

Section		$2h = 12$	$2h = 10$	$2h = 8$	$2h = 6$
(*A*) *Inter-electrodal* ($x = 5$)					
x/h	=	0·833	1	1·25	1·66
K' for half the inter-electrodal space from Fig. 17	=	0·375	0·46	0·583	0·793
$2K'$	=	0·75	0·92	1·166	15·86
Total ($13·6 \times 2K'$)	=	10·2	12·51	15·85	21·6
(*B*) *Lateral margins* ($x = 9$)					
x/h	=	1·5	1·8	2·25	3
K' (each margin)	=	0·36	0·4	0·45	0·505
$2K'$ (two margins)	=	0·72	0·8	0·9	1·01
Total ($13·6 \times 2K'$)	=	9·8	10·88	12·22	13·72
(*C*) *Bottom margin* ($x = 11·1$)					
x/h	=	1·85	2·22	2·78	3·7
K'	=	0·405	0·445	0·49	0·545
Total ($10 \times K'$)	=	4·05	4·45	4·9	5·45
$(A + B + C) = \Sigma K'$	=	24·05	27·84	32·97	40·77
$K = 0·02K'$	=	0·481	0·5568	0·659	0·815
K'' (measured)	=	0·485	0·535	0·61	0·764
$k = K''/\Sigma K'$	=	0·02	0·0193	0·0185	0·0188

APPENDIX 1.

Some Remarks on the Method of Procedure in the Experimental Work.

(1) In order to equalize the deposit on both electrodes as much as possible, the current was reversed in the cell roughly every 30 minutes, which was about the duration of each test.

(2) The temperature of the electrolyte was observed at the beginning and end of each test. Owing to the large volume of liquid used, the actual rise of temperature was not more than 3 degrees C.

remained constant, but in some tests, especially with higher values of current, slight variations of P.D. or current were apt to take place in such a manner that their ratio was no longer constant, indicating a variation in the conductance of the cell. Since the temperature-rise was small and the concentration was kept constant, it was considered unlikely that such fluctuations would arise from changes of the resistivity of the electrolyte, but rather from variations of contact resistance at the electrode surface, caused chiefly by the formation of gas bubbles. It was therefore decided to keep the current rigorously constant, in order to maintain a constant potential difference at the boundaries of the

electrolyte, which is essential for the purpose of comparing observations with mathematical results, and to note the variations of P.D. as they occurred.

(6) If tests taken at different times be compared, a slight difference may be observed in the results. This is due to alteration of the surface condition of the electrode by electro-deposition, which has the effect of altering, sometimes appreciably, the conductance of the cell.

APPENDIX 2.

Determination of the Conductivity of the Electrolyte.

The apparatus employed is somewhat similar to one used by S. W. J. Smith * and H. Moss for the same purpose. It consists of two bottles connected near their bottoms by a horizontal tube (see Fig. 19). The bottles and connecting tube contain the electrolyte whose conductivity is to be measured. Current is sent through the electrolyte by means of electrodes placed in the bottles. Two auxiliary electrodes are inserted in the tube near its ends and connected to an electrometer by means of leads which pass through two mouths having rubber stoppers in the tube. The fall of potential across the electrolyte in the tube is measured on the electrometer and the reading compared with that across a known resistance; in this way the required resistance is found.

* *Proceedings of the Physical Society of London*, 1913, vol. 25, p. 133.

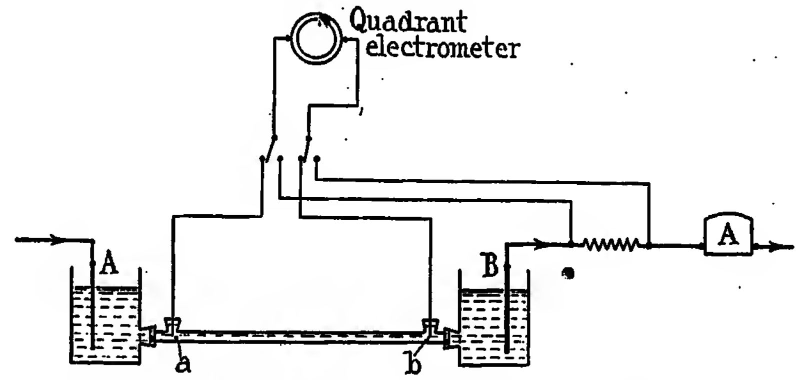


Fig. 19.—Apparatus for measuring the conductivity of an electrolyte.

The internal cross-sectional area of the tube is determined from the mass of distilled water which would fill a measured length of the tube.

Various readings were taken for different currents, giving consistent values of the resistance of the electrolyte. The conductivity works out at 0·0202 mho/cm^3.

RAILWAY ELECTRIFICATION IN FOREIGN COUNTRIES.

By Stanley Parker Smith, D.Sc., Member.

(Abstract *of a Lecture delivered before* The Institution *3rd January, before the* Western Centre *7th January, before the* North Midland Centre *22nd January, before the* South Midland Centre *16th January, and before the* Scottish Centre *12th February*, 1924.)

As I wish to treat the subject of railway electrification as objectively as possible, I propose to deal with the various countries in alphabetical order. It will be noticed from the title that I propose to consider only what has been done in foreign countries; in fact there is nothing to say about the electrification of long-distance railways in Great Britain.

Austria.

I wish to give some idea of the work that has been going on largely since the war. Before the war Austria had already had experience with electric railways, and just prior to hostilities the line known as the Mittenwald railway, which runs from Innsbruck to the German frontier, then into Bavaria, back again into Austria and so on to Reutte, was built as an electric railway and equipped on the single-phase system. The frequency was raised from 15 to 16⅔ cycles, in accordance with the common practice of Germanic countries. This is a privately-owned railway. The power is obtained from the station at Rutzbach, which is now also supplying the power for the Arlberg Railway. Another railway which was running before the war was the pilgrim and tourist line from St. Pölten to Maria Zell. Originally this was a steam line. It was converted to electric working in order to increase the traffic facilities, and it has been a success ever since it was opened. There are several water-power stations, and at St. Pölten there is a Diesel engine station run from Galician crude oil. Another railway which was opened just before the war—also a private line—runs from Vienna to Pressburg in Hungary. This line is a direct-current line at the termini, while single-phase locomotives haul the trains in the open country.

The position of Austria after the war was a very serious one, and it was therefore important to utilize

her water power in order to reduce coal imports. The country is very mountainous, and water power is fairly plentiful. The worst problem the Austrians had to face was the Arlberg line which connects the route from Lake Constance to the capital through Innsbruck —the main east and west route through Austria. The Arlberg Tunnel gave considerable difficulties in the old dual monarchy, but for various reasons, particularly strategic, nothing was done in the way of general electrification. This line was commenced first. The hydro-electric station at Spullersee is fed from a large storage lake, which can be drawn on during peak loads, frosty weather and droughts, and serves also as a general reserve. This station will work in parallel with the Rutzbach station.

In July 1920 the National Convention decided on a general electrification scheme and made a five years' programme for the conversion of the Arlberg, West, Tauern and Salzkammergut lines. In July of last year (1923), the Innsbruck end of the Arlberg line was opened for electric working. It is interesting to mention that the 55 000-volt supply cables, instead of being taken through the tunnels, are led over the Arlberg and Korntauern passes. These passes are often inaccessible in winter so that the construction has to be very rigid.

The system which the Austrians chose was the single-phase system with 15 000 volts at the contact wire, and a frequency of $16\frac{2}{3}$ cycles. They had had previous experience with that system, and were accustomed to the manufacture of the machinery. They also found that for various reasons it would be the most economical one. The power is to be supplied mainly by railway generating stations, though in the south power may be bought from private companies. Generally speaking, however, the Federal railways are equipping their own stations.

France.

The scheme commenced by the French since the war is probably of much greater extent than that of any other country. Their experience of coal shortage and the need for using the natural resources have probably had considerable influence in urging their decision to make rapid progress with railway electrification. Before the war a certain amount of work on the single-phase system had been done by the Midi group, chiefly on lines running into the Pyrenees. This was successful, but in accordance with the decision which was ratified by the French Government, that work has now been converted into the national system, which is direct current at 1 500 volts. This system is to be used for the Midi, the Orleans, and the Paris, Lyons and Mediterranean Railways. The power for these railways is to be obtained from a national three-phase, 50-cycle, 150 000-volt network. Water power will be utilized wherever possible. There is a great deal of power available in the Pyrenees, in the Massif Central (Central Plateau) and in the Alps. In addition to this immense water power resource, there are large steam stations at Paris, Gennevilliers (which has been recently opened) and other stations in the course of construction. Where the distances are shorter, transmission voltages lower than 150 kV will be used. The pressure will be transformed down and converted either by means of 1 500-volt, 50-cycle rotary converters, by mercury rectifiers, or by the older method of using two 750-volt rotary converters in series. As these matters have been recently described before the Institution,* it is not necessary for me to dwell very long on France. It may be well to say that the scheme is simply enormous in extent. Each of these railways is contemplating something like 2 000 to 3 000 km of route electrification, so that the 20 years' programme which they have arranged is perhaps something that no other country has hitherto attempted.

As regards the work already done, the Paris–Orleans route is now electrified for a considerable distance. The Midi is probably further ahead than any. On the P.L.M. very little has been done as yet. The Culoz–Modane line has been chosen as the experimental section, and it is hoped next to get on with work round Nice, and on the Côte d'Azur.

With regard to the locomotives, the goods engines are pretty well standardized, mainly on the American model, while for the express locomotives the French are building a large number of types for experimental purposes.

With regard to the mode of collection, it is not the object of this lecture to open up or continue any of the academic discussions which we have from time to time; but one question of perennial interest, in common with the choice of system and whether power should be generated by the railway companies or obtained from supply authorities, is whether the current should be collected from a third rail or from an overhead wire. With a d.c. pressure of 1 500 volts it is exceedingly difficult to decide which is the better method. The French therefore decided that all the rolling stock should be made available for collecting the current either from an overhead wire or from a third rail. The result is that many of the lines are using both methods; but some of the lines appear as much prejudiced in favour of the overhead system as other lines are prejudiced in favour of the third-rail system. I mention this to show that just on the border-line of 1 500 volts d.c. it is almost impossible to know what to do; one can get as many divisions of opinion on that as on any other sharply divided subject.

Germany.

Before the war Germany had already started in Prussia, in Bavaria and in Baden to experiment on electric traction, using the single-phase system. In 1920 the German railways, which were previously State railways, were federalized. The Reich immediately set on foot an inquiry into what system should be adopted for the electrification of the railways, because the condition of the coal supply was not much easier in Germany than it was in her neighbouring countries. The result of the inquiry was to confirm the use of the single-phase system. That system had been adopted already and they found it would be best to continue with it, except for the Berlin railways. It was originally intended to make Berlin part of the general scheme in order to utilize

* *Journal I.E.E.*, 1924, vol. 62, p. 213.

existing rolling stock, but that scheme was found to be unsuitable owing to the enormous post-war increase of traffic, which made it necessary to use motor coaches. In view of this it was found more desirable to use direct than alternating current, as the service could be made denser and more in accordance with suburban needs. Further, the equipment for motor coaches was cheaper with direct than with alternating current. It was therefore decided to equip the urban, suburban and ring lines of Berlin with 800 volts (d.c.), third rail. The rest of the system is to be single-phase throughout. It is not easy to state to what extent Germany's decision to use the single-phase system led France to use a different system, but it would be reasonable to assume that the two countries would not adopt the same system.

As so much has been said in connection with interference with communication circuits, it is rather interesting to note that in France it was given as one of the decisive factors that direct current causes less disturbance to communication circuits than does alternating current. In Germany disturbances had, of course, been caused by alternating current, but here the argument was that in any case it is unsound practice to have a high-tension overhead wire near a communication circuit. In other words, the Germans consider that the right procedure is to remove the communication circuits from the track. When once the telephone wires are removed it does not matter, of course, which system is used, from this point of view. Thus one country gets over the interference trouble by using direct current, and the other by removing the communication circuits from the track. In trying to determine which system is really the better financially (both systems are technically sound), a great deal depends on such subsidiary questions as how much it will cost to remove the communication circuits when alternating current is used, and how much the prevention of electrolytic troubles with direct current will cost.

Coming to the Prussian lines, the Silesian mountain railways are worked from the steam station at Mittelsteine, and have been extended considerably since the war. In Saxony there is the experimental track Leipsic–Halle, etc., in an important industrial district. Power is supplied from Muldenstein—a station worked with lignite fuel too poor for steam locomotives.

The Wiesental line in Baden has been working for some years. It is really a small valley line electrified for experimental purposes, and is fed from a hydro-electric station at Augst Wyhlen on the Rhine.

In Bavaria an enormous 100-kV ring main encircling the country from Munich to Nuremberg is being erected. Power will be mainly obtained from a large hydro-electric station at Walchensee and from stations on the Middle Isar River. These stations will all be linked up. When this scheme was under consideration, the railways obtained rights to put down their own pipe lines and their own generators in the stations then being built for the Bavarian ring main. These stations are therefore divided into two distinct portions, a traction part (single-phase) and the general network part (three-phase). It was more economical to obtain traction power in that way than to build separate stations: otherwise the systems are independent. The traction energy is generated in the form of single-phase current at $16\frac{2}{3}$ cycles, so that for the track it only needs to be transformed down in the substations to 15 000 volts.

About 10 or 15 years ago gears were very little used in locomotives; in fact they were then in but a semi-developed state. Germany tried almost every conceivable arrangement with side rods and cranks. The methods that were used in America did not seem to be very popular in Europe. Now there is, as we have seen, much greater freedom. In France gearless locomotives are used with the armatures on the axle, and the geared quill drives are also becoming very popular. Later, gears with side-rod systems began to be used in Germany, while the Austrian types are very similar. Germany has now more or less standardized her drives, and only one of the six standard locomotives is without gears. This gearless locomotive has proved very satisfactory, and is being kept for express work; but for all the other cases it is cheaper to have a geared locomotive. We have to remember, however, that gearing was not altogether feasible some years ago. Attention may be drawn to the individual-axle drive, due to Buchli, which was developed in Switzerland, where it appears to have been a success. It is now being tried both in Germany and in France, sometimes with alternating and sometimes with direct current. This drive has proved very attractive: it overcomes in a very practical manner the difficulty of transmitting the power from a spring-borne motor to a non-spring-borne wheel.

HOLLAND.

It was originally intended here to use single phase—indeed a short single-phase line has been working for some years from Scheveningen to Rotterdam; but on further consideration the Dutch decided that as they wanted to utilize the existing power stations and as the distances were relatively short (Holland being a small country) it would be better for their purpose to use 1 500 volts d.c. One of the decisive reasons was that in Holland the railways are extensively used for telegraph and telephone circuits, and it would be a matter of some difficulty to remove them. They have decided, therefore, when they proceed, to use the d.c. system. The first line that they hope to electrify when necessary is from Rotterdam to Amsterdam.

HUNGARY.

This country has practically no water power and very little coal resources. It has no locomotive coal, and yet it must do something to make itself independent of imports. The scheme that is being put forward is to have a national three-phase, 50-cycle network, obtaining the power from fuel stations fired with brown coal (lignite) or peat. The power for the railways would then be obtained by taking separate phases along the various routes so as to equalize the load as reasonably as possible. The standard a.c. commutator motor for traction work at the present time is that known as

the "neutralized-series" motor, but for successful working a low frequency is necessary and it would not be suitable for use on such a 50-cycle system. I think that one reason why some countries in Europe have been so successful with alternating current is because a lower frequency has been adopted. For instance, $16\frac{2}{3}$ instead of 25 cycles is used on the Continent. Hungary, however, wishes to use 50 cycles, and for that purpose the a.c. commutator motor is not a success as a traction machine. It is hoped, therefore, to overcome the difficulty by using what is known in America as the "split-phase" system. On the locomotive a phase converter is to be used to supply the three-phase induction motors used for driving the locomotive. The system is in successful use in America.

Italy.

This country is really the cradle of railway electrification in Europe: the Valtellina railway was about the first example of European main-line electrification. At that time the three-phase system was practically the only system available. The d.c. arrangement then was in its infancy for main-line work, and the single-phase system had not yet proved a success. The three-phase system entails a double overhead conductor, but when this is said its worst disadvantage has been mentioned. A frequency of 15 cycles was adopted for two reasons. The inductive drop was small, but perhaps the more important matter was that the speed of the motors was more suitable. Gears were not used on locomotives at that time; they were a later development, so that in the early years of this century when Italy began to electrify her railways there was good reason for adopting a low frequency of 15 cycles in order to get a suitable speed for her gearless locomotives. This conversion proved a success, and in 1909 and subsequently the railways known as the Giovi lines were electrified. These have the heaviest train-movement in Italy. There is an enormous traffic from Milan to the port, and in crossing the Apennines there are many tunnels. The Giovi tunnel had a very bad reputation for foulness, and electrification has solved that problem completely. The line from Savona to Ceva, on the way to Turin where the railway crosses the Apennines, was also electrified. The Mont-Cenis line was next tackled and for some years now the tunnel has been worked with three-phase locomotives. There has thus been a tremendous amount of work done with three-phase electrification in Italy. It is easy to criticize this system now that we have other systems which are perhaps simpler and, as we may think, better, but we are trying to look at the matter as objectively as possible, and I think he would be a bold man who would say that Italy had not done well with her three-phase system. It has solved practically all her difficulties. The earlier motors, it is true, ran at only two speeds, but there are now locomotives that will run at three or even four speeds and which appear to fulfil the conditions of the service admirably. It is true that, with the double overhead wire, the voltage has hitherto been kept rather low (about 3 000 volts), but nevertheless I think the greatest credit has to be given to the Italian engineers for their pioneer work in developing a system which up to this day has not had to be replaced.

Future work will extend into the Peninsula. In the Rome district the standard frequency will be 45 cycles and the power will be taken from the existing networks. A higher voltage will be used on the track. Thus it is intended to try the three-phase system at 45 cycles and 10 000 volts with geared locomotives.

Scandinavia.

This is a Germanic country and we must not be surprised to find alternating current used again. The Riksgränsen line has been worked electrically for some years. It is the most northerly railway in the world and lies practically within the Arctic Circle.

This Lapland railway was built for transporting the rich minerals mined at Kiruna and Gellivare. There is a considerable heavy traffic down to the port of Lulea on the Gulf of Bothnia and to Narvik on the Arctic Ocean. The power is obtained from a hydro-electric station at Porjus. The electrification is now being extended through the Norwegian part from Riksgränsen to Narvik by what is known as the Ofoten railway, so that soon the whole railway will be electrified.

The Swedes have also been working a good deal at the electrification problem of the Stockholm–Gothenburg line, and have decided that the best system for their country is a single-phase overhead $16\frac{2}{3}$-cycle, 15 000-volt one. The power will be obtained from stations which are used for general industrial work.

In Norway a little has been done. The Drammen railway was electrified at the same time as the gauge was altered, so that at that time there was a good deal of complication. Two light railways also are electrified, while the extension of the Riksgränsen Railway to Narvik has already been mentioned.

The original Riksgränsen locomotive had no gears, developed about 1 700 h.p. and weighed about 138 tons, while the new geared locomotives give 2 900 h.p. and are about 10 tons lighter than the original.

Switzerland.

Of all countries probably Switzerland has done relatively the most with regard to her electrification schemes. In fact she is going ahead with it so rapidly that recently, when the unemployment question became so acute and it was necessary to do something to keep her works busy, she hastened the programme by 5 years, so that the work which was to have been completed by 1933 has now to be completed by 1928. This will entail the electrification of about 200 km of route per annum instead of about half that amount. Years ago they commenced experiments in Switzerland and, as in other countries, the privately-owned railways were well to the fore. One of the oldest electrifications is the Burgdorf–Thun line, which was electrified on the three-phase system. Next came the Simplon Tunnel, which was equipped with the three-phase system for practical reasons, three-phase power being available from the tunnel workings. They were also able to take a couple of locomotives which were being built for the Valtellina railway.

During the war, conditions were very serious, owing to coal shortage in Switzerland, and they therefore pushed forward the three-phase electrification as far as Sion in the Rhone Valley. The Loetschberg line was electrified from the outset. It was built to connect Berne with Italy, and was equipped on the single-phase system.

The group of privately-owned lines, known as the Rhaetian Railways, is now completely electrified on the single-phase system, power being bought from local supply authorities.

As regards the Federal Railways, the matter has been subject to a good deal of consideration by a special Investigatory Committee, and it was ultimately decided to recommend the single-phase system with a high-voltage overhead contact wire and a low frequency. There was a good deal of argument for a long time, and when, during the war, they really had to begin to electrify the St. Gothard route they still did not decide on what they were going to do until the works at the Ritom power-house were so far advanced as to make a decision imperative; and then it was decided in favour of the single-phase system. Successful results were being obtained on the Loetschberg railway and on the Rhaetian group: in addition, their manufacturers were accustomed to the system, so that they could go ahead without hindrance. The whole of the St. Gothard line is now worked on the single-phase system, the supply being taken from the Ritom and Amsteg stations.

With regard to new work, there is the Rhone Valley line, including the conversion from the three-phase to the single-phase system, and the new station at Barberine.

An immense variety of locomotives have been tried in Switzerland. Some of these have been provided with regenerative equipment, but without very good results. The place where one needs regenerative control—on the suburban lines—is just where it is so difficult to get it. On Swiss lines so little energy is returned that it is almost better to use rheostatic braking, considering its greater simplicity.

A few remarks as to the method by which the Swiss intend to equalize the load, i.e. to get a regular supply of power, may be of interest. The station at Ritom is on the southern side of the St. Gothard Tunnel. There is a lake which collects water in summer. This is drawn on in winter and during peak loads. The other station at Amsteg is fed from the river Reuss on the nothern side of the St. Gothard Tunnel. The water is taken five miles through a pressure tunnel in the hillside, and then goes down a pipe line to Amsteg. In the winter there is not much water in the river, so that this station is mainly for summer traffic. Until the line is electrified up to Basle, these stations will not be fully loaded, so that in the meantime the Federal authorities are installing three-phase generators which will work on the neighbouring general supply networks. Generally speaking, however, the idea is to use their own stations for the railways, and as the railway load develops, the single-phase generators will take the place of the three-phase machines. The stations will then be used for traction solely, and will belong to the Federal authorities.

UNITED STATES OF AMERICA.

In the west there is the Chicago, Milwaukee and St. Paul Railway which was opened for electric working during the war. There is no need to say much about this line as a description illustrated by cinematograph films was given here last year by Mr. Welbourn (see vol. 61, p. 800), and I do not suppose that any line has been more widely advertised. It is the longest electrified railway in the world, and it was originally unique in so far as it uses direct current at 3 000 volts. Previously the highest d.c. voltage had been on the Butte-Anaconda line (2 400 volts), for taking the copper ore from Butte to the smelting works at Anaconda. The C. M. & St. P. Railway is a trans-continental route from Chicago to Puget Sound. Starting at Harlowton, the electrified portion crosses five ranges of mountains. Already the two heavy-grade sections from Harlowton to Avery and from Othello to the Puget Sound termini have been electrified, 650 miles in all. Ultimately nearly 900 miles will be electrified. It is a single track with very few trains per day, but these are very heavy. The locomotives are of about 3 000 to 4 000 h.p. and weigh 200 to 300 tons. The power is bought from supply authorities owning hydro-electric stations, the peak load being definitely limited. This is a fine and interesting experiment with high-voltage direct current, and it had an enormous influence on the French in their decision to use direct current, though they decided to use half the voltage.

In the west there is also the Cascade Tunnel electrification—the only three-phase case in the States—and the single-phase railway at Spokane.

Coming to the eastern portion of the States, there are various tunnel electrifications. Where the tunnel is not a terminus the electric locomotive is simply hitched on to the steam locomotive and pulls the whole train through. At termini the steam locomotive is replaced by an electric locomotive to haul the train through the tunnel.

The Norfolk and Western Railway is a heavy mineral line. In addition, there is the neighbouring Virginian Railway which they have now decided to electrify. It is practically the only electrification started in the States since the war, but it is a very large scheme involving a contract of 15 million dollars. The Virginian Railway, like the Norfolk and Western Railway, is to be electrified on the split-phase system. Coal trains up to 9 000 tons will be hauled by locomotives giving 12 000 h.p.

The electrified lines in the east are chiefly centred about New York and Philadelphia. Some of these railways are very much like the suburban railways round London, with very dense traffic, and operate at 650 volts d.c. The New York, New Haven and Hartford line works on the single-phase system at 11 000 volts and 25 cycles. Probably more single-phase development work has been done on this than on any other line. The locomotives work under the disadvantage that they have to enter New York along the New York Central tracks, so that the single-phase motors have to be adapted to work on direct current also. The result is a compromise, for a single-phase motor cannot be made to

work at its best on direct current, any more than a d.c. motor can be made to work at its best on alternating current. The Pennsylvania Railway has electrified some d.c. lines and also some a.c. lines. There is a scheme ultimately to extend the a.c. system to New York and to Washington.

Passing now to the locomotives, the individual-axle drives are the best known. One gearless type employs the nose or tram suspension for the motors, even for the very largest locomotives. In another arrangement a motor armature is mounted on every driving axle. A further type employs a quill round the driving axle, and the motors may be either gearless or geared. Twin motors have become very popular in the geared drive, the two motors being connected in series in order that double the voltage may be used. Side rods are, or will be, used on locomotives on the Pennsylvania, the Norfolk and Western and the Virginian lines.

On the split-phase locomotives there is a phase converter which converts the single-phase current into three-phase current for the three-phase induction motors which drive the axles through gearing.

Conclusion.

I feel that we ought to know as much about railway electrification as possible, because it is a matter that may affect us very seriously in this country.

We have seen enormous developments in the employment of hydro-electric power. I think that this may affect us in two ways. It may in years to come decrease our coal exports, which is of course a matter of national concern, and on the other hand it shows us that there is an enormous amount of electrical development going on throughout the world in connection with both hydro-electric and railway equipment. I do not think that it matters much what the system is, but my feeling is that, whatever the work may be, our firms ought to see what they can do to take part in this great development. For this reason, they should be given facilities for obtaining experience on home railways—e.g. on single-phase equipment, by extending the electrification to Brighton; and on direct current by proceeding with the scheme on the North-Eastern Section of the London and North-Eastern Railway.

Discussion before The Institution, 3 January, 1924.

Lieut.-Colonel F. A. Cortez Leigh: The author mentions that in France it has been decided to electrify the railways on the d.c. system at 1 500 volts, and that the overhead system has been adopted for the greater part of the work, although the third-rail system is to be used in certain sections. Can he tell us why the overhead system was not continued throughout, as I understand that most of the work has been done in conjunction with the Government? The majority of recent main-line railway electrification schemes have been carried out in countries where water power is available, and this would point to the fact that the availability of ample water power has been the determining factor. I should be glad if the author would confirm this view. What is the proportion of passenger traffic working to freight working in those countries, and what is the actual kilowatt-hour consumption for the two classes of traffic? Another point on which the author's views would be most interesting is as to the reason why the unusual frequency of 45 cycles has been adopted in Italy, instead of that in use in neighbouring countries.

Mr. G. W. Partridge: I am of the opinion that the principal factor which will determine what particular system shall be used for electric traction is not so much what will be the interference effect or the watts per ton-mile, or even the efficiency, but what is the cheapest system which will transmit the energy from the point where it is generated to the draw-bar of the train. Can the author say what is the distance between the a.c. substations in Austria and in Germany? I should also be glad if he would say if it is possible to design a motor which will work reasonably well with both single-phase and direct current. I have seen small motors working satisfactorily and I should like to know whether in the future it will not be possible to have larger motors which will work on the two systems and give reasonably efficient results.

Mr. T. Stevens: Twelve years ago I was asked to go to a foreign country to lay out the electrification of a railway from water power. I came to the conclusion that there was very much more profitable use for all available water power than was obtainable from the railway. I recommended that the railway should still be operated by steam and that all the output of water-power plant should be sold in near-by towns. I cite this case because the electrification of railways is, as just mentioned by Mr. Partridge, a question of economics. If, as was shown in one case in the discussion on Mr. Bachellery's paper, 24 per cent per annum on the capital outlay for electrification can be saved thereby, it is worth while investing that capital. Where only 5 per cent can be saved, as was also then shown in connection with another railway, electrification should not be undertaken unless there are other substantial reasons to warrant that expenditure of capital.

Mr. W. E. Highfield (*communicated*): Quite apart from the economic advantages to the railways, there is an important reason why main-line electrification should not be delayed. We are an exporting nation, and electric railway manufactures are an important item of our exports. So far we have no great reason to complain; France, Japan, South Africa, Australia and New Zealand have all purchased electric railway material in this country. But it is a definite disadvantage to manufacturers to have no English railways supplied with their material. It is an advantage to be able to exhibit such a system but—and this is even more important—it keeps the manufacturer continually in touch with railway requirements and conditions. This advantage to the industry would be lost if the railway companies adopted the policy of manufacturing their own electrical gear. That policy was adopted in the case of steam locomotives and it practically killed the manufacturing industry. As the author has stated, the battle of the systems is finished. From the manufacturers' point of

view it is desirable that we should be able to compete in the world's markets both for single-phase and direct-current material, since it seems certain that both systems will be used impartially all over the globe. It would therefore be desirable to use both systems in this country. The main difficulty is the strategic one, for it is unthinkable that the systems should be such that free intercommunication would be interfered with. Prior to the adoption of 50 cycles by the British Engineering Standards Committee, no manufacturer would have offered a 50-cycle, 1 500-volt rotary converter on one commutator. These rotary converters are now in successful use, but it was the Committee's action that forced the manufacturer to meet the demand. If interchangeable running were insisted upon it might equally force a solution. If the technical difficulties cannot be overcome, the solution may be found to lie with the traffic departments, whose views are not, in my opinion, made sufficiently public. If these were more generally made known they would modify many opinions on the subject of main-line electrification in England.

[Dr. S. P. Smith's reply to this discussion will be found on page 324.]

North Midland Centre, at Leeds, 22 January, 1924.

Mr. P. Furness : I noticed in the lantern slides that the locomotives have straight-cut gears which I should expect to be very noisy. Has there been no development of the helical and double helical gears on the electrical work which the author has described ?

Mr. R. M. Longman : In some of the slides shown, the American locomotives apparently have outside seats on the front, and I should like to know for what they are intended. I thought that a considerable portion of the New Haven and Hartford lines had been changed over to direct current as a result of the controversy on the subject during the first few years of operation. When one bears in mind the numerous papers on the subject of railway electrification which have been discussed before this and other Institutions in this country, it is rather surprising that we have made so little advance. Can the author tell us what results have been obtained with the main-line electric locomotives which were so much referred to by Sir Vincent Raven about a year ago, and can he also give us any information regarding the operation of the mercury rectifiers on the French railways ?

Mr. A. F. Carter : I should be glad if the author would say whether difficulty is experienced in the collection of current from the line in snow-bound countries. Some of the electric locomotives require several thousand horse-power, and I have noticed that difficulties are occasionally experienced in this country when taking only about 150 h.p. from the line. Another interesting problem when taking electrical energy for traction from public supply stations is the maximum demand. It seems to me that for a locomotive suddenly to take 2 000 or 3 000 kW from a station of possibly only 10 000 kW or less capacity for perhaps half an hour, two or three times a day, would not be conducive to goodwill and efficiency.

Mr. M. Wadeson : I had the idea that there was a lot of railway development under way in this country and that British manufacturers were doing and had done quite a lot of railway work ; but I rather gather from the author's remarks that practically nothing is being done in this respect.

[Dr. S. P. Smith's reply to this discussion will be found on page 324.]

Scottish Centre, at Glasgow, 12 February, 1924.

Mr. M. Blacklock : Economic considerations have to some extent caused Continental countries to electrify their main lines. Many of them are short of coal and do not possess the comparatively cheap supply which is available in this country. The author states that the adoption of electrification results in a saving of about half of the coal which would have been consumed in a steam system. To save 25 lb. of coal per mile is very desirable, but is it not possible that this saving will be more than swallowed up by very high standing charges, particularly in the case of lines which have no very great density of traffic ? I gather from the lantern slides that the angular connecting-rod drive is being discarded in favour of the geared drive with coupling rods. The electric locomotive of the future will apparently bear some sort of resemblance in its running gear to the well-known features of the steam locomotive. Electrification seems to be bound up with the question of density of traffic. If it is contemplated to equip the whole of the country with superstations and substations, and to electrify every mile of line and every siding, it is obviously a gigantic undertaking and one which cannot be undertaken lightly or without due consideration of the question in all its bearings.

Mr. G. G. Braid : Britain has been the birthplace of many scientific inventions, but it has often been left to other countries to develop these inventions on a commercial scale. There may perhaps be some advantage in this ; we learn something from the successes of others, but, I think, a good deal more from their failures. The general tendency of all heavy electrical engineering is to use higher and higher voltages, and hence it seems to me that the two best systems of electric traction are the direct-current system with 3 000 volts on the overhead conductor—such as is used on the Chicago, Milwaukee and St. Paul Railway—and the single-phase system with 15 000 volts on the overhead line as in Germany, Austria, Switzerland and Sweden. The 3 000-volt d.c. system has several advantages over the 1 500-volt system. The substations can be placed much farther apart, and only half the current has to be collected from the overhead conductor. I think that this country, as well as France,

has been rather conservative in proposing direct current at 1 500 volts for main-line electrification. The cost of electrifying the lines in sparsely populated districts will probably be prohibitive, whereas direct current at 3 000 volts or alternating current at 15 000 volts would be more economical. It would be an advantage to adopt both systems. Circumstances will, however, usually determine which system should be used. The ultimate question to be answered in every case is: "Will it pay?" The author suggests that, for political and military considerations, France has adopted a different system from Germany. Possibly for the same reason all the central countries of Europe have adopted the same single-phase system at $16\frac{2}{3}$ cycles per second with 15 000 volts on the overhead conductors. It seems to me that Germany has been more far-sighted than France in this matter, for whereas it is quite possible to adapt an equipment which runs efficiently with single-phase commutator motors over the 15 000-volt lines, so that it may run in the case of emergency over a 1 500-volt d.c. line, or, indeed, off one of the phases of a three-phase line, it would be impossible to adapt an equipment primarily designed for 1 500 volts direct current so as to operate over a single-phase line at 10 times the voltage.

Mr. J. D. Peattie (*communicated*): Is there any tendency to use direct current at voltages comparable with those adopted for single-phase schemes? My reason for asking is that up to the outbreak of war I was engaged with one of the large Continental firms on some high-voltage d.c. investigations. One of the objects was to examine the possibilities of working at much higher d.c. voltages for long-distance railway electrification. At that time we were in the midst of the difficulties encountered in the developments of single-phase traction, particularly with the switching and control of the low-tension currents of the order of 2 000 amperes on the locomotive itself between transformer and motor. I worked for the most part with two machines, and a few figures regarding these may be of interest. The first gave 36 000 volts (d.c.) and, since then, machines working on the same principle have been built in America up to 100 000 volts. They have been used for blast-furnace dust-precipitation plants. The second machine was built primarily to test a commutation device and gave only 4 000 volts (d.c.). Its other characteristics were, however, quite extraordinary. For instance, the measured commutating reactance voltage per segment was 95 volts at full load. I notice from the Press that Dr. Scherbius has again raised the question of high-voltage d.c. transmission, and, as the high-voltage d.c. system for railways appears to offer many possibilities, I should be glad if the author would state whether developments along these lines appear to be likely.

Dr. S. Parker Smith (*in reply*): In reply to Col. Cortez Leigh, although the French Government initiated the electrification schemes, details were left to the technical commission, which found itself undecided on the question of current collection and in consequence advised that all electric rolling stock should be fitted with both methods of collection. It would be wrong to associate railway electrification too closely with water-power utilization, though this has undoubtedly been a prime factor where coal is scarce. In very many instances other factors such as economy, congestion, smoke troubles, etc., have been decisive. A good idea of the kilowatt-hour consumption can be obtained from many of the reports presented to the recent International Railway Congress in Rome. The choice of 45 cycles as the standard in South Italy arises from the fact that frequencies of 42 and 50 cycles are almost equally common in those parts, and 45 has been chosen as a mean value.

In reply to Mr. Partridge, substation spacing is a question not only of voltage but also of geographical and topographical features of the route, grades, location of junctions, branches, etc. On the Arlberg route there are stations 40 km apart, while on the Leipsic-Halle route the intervals are sometimes 60 km. It is possible to build a.c. motors which will work satisfactorily on direct current, but not conversely. The compromise, however, does not give the best motor.

In reply to Mr. Furness, both helical and double helical gears have been used on electric locomotives.

The New York, New Haven and Hartford Railway is equipped on the single-phase system, but the locomotives have to enter New York on the New York Central lines which are on the d.c. third-rail system. Possibly this is what Mr. Longman has in mind. Apparently the work commenced by Sir Vincent Raven has been suspended—no published results are known to me. Mr. Longman will probably find the information which he needs on the operation of mercury rectifiers in Mr. Bachellery's paper and the discussion thereon.*

In reply to Mr. Carter, little trouble is experienced with snow on overhead contact lines. Also with the under- or side-contact third-rail system the difficulty is not serious unless the snow is deep. To keep the maximum demand within pre-arranged limits, current-limiting devices are often used; for example, on the Chicago, Milwaukee and St. Paul Railway.

Mr. Wadeson is correct in assuming that British firms are doing a fair amount of railway electrification, but the bulk is much below our capacity.

In reply to Mr. Blackwell, cases may and do arise where electric traction is used, although it is more costly than steam. Independence of foreign supplies and the reduction of imports, however, have also their economic value, while many technical reasons may make electric haulage the more desirable.

In reply to Mr. Peattie, work is also being done in this country with high-voltage direct current, e.g. on the transverter system, but hitherto a high-voltage d.c. motor suitable for installing on locomotives has been wanting. In this respect, the a.c. system has the charm of simplicity.

* See pages 213 *et seq.*

ELECTRIC PASSENGER LIFTS.

By H. MARRYAT, Member.

(*Paper first received* 28*th July, and in final form* 20*th November*, 1923; *read before* THE INSTITUTION 17*th January, before the* NORTH-WESTERN CENTRE 8*th January, and before the* SOUTH MIDLAND CENTRE 20*th February*, 1924.)

SUMMARY.

The author makes a plea for British investigation and design in order to produce a lift more especially suitable to conditions in this country than is possible by following American practice too closely. A number of problems requiring investigation are referred to. The essential parts of a lift and the factors of cost are stated. The advisability of consulting specialist engineers with regard to new construction is suggested. A complaint is made that lift makers are often consulted too late in the development of a new building to enable them to offer the best and most economical scheme. It is maintained that a lift service is more important than the provision of stairs.

The methods employed by the author in calculating the lift capacity required in a building are outlined. A plea is advanced for the employment of lifts of higher running speed and improved acceleration, and the method adopted by the author in an investigation of acceleration problems is described.

A comparison is made between drum and sheave driving. The effects of the position of the winding engine and of rope-reeving upon maintenance cost are discussed. Types of worm gearing and methods of control are described and the limitations of automatic control emphasized. Micro-drive and decelerator devices for attaining automatic floor levelling are detailed and reference is made to a new system of control—the "Auto-Pilot."

Safety devices employed in connection with passenger lifts are described, and the record and infrequency of accidents are discussed and commented upon.

A lift is a machine designed to transport a load from one level to another in a vertical or nearly vertical direction by means of a suitably guided car or platform.

Electricity was first used to operate a lift about 1885, and since 1893 has been increasingly employed for the purpose, until now, where electricity is available, it has practically superseded all other forms of energy for new construction. Existing hydraulic lifts are rapidly being converted or replaced by electric lifts. Except where certain special conditions prevail—for instance, short travel and heavy load—when the direct-acting hydraulic lift offers certain advantages, the electric lift has proved itself to be the most economical and convenient machine yet designed for the purpose. This statement being accepted in principle, it will not be necessary to enter into a comparison between electricity and other forms of energy for operating lifts.

The electric lift is becoming an increasingly important feature in modern buildings. The tendency of the great and increasing commercial population of cities to congregate in central areas, and the corresponding increase in site values, are bringing about a continual replacement of older and smaller buildings by newer and larger ones, in which by means of lift service it is possible to take the utmost advantage of the upper floors. Again, the tendency to work shorter hours and at higher speed reinforces the demand for a rapid lift service to replace stairs. It is, therefore, perhaps remarkable that so little has been written or published upon the subject in this country, although there are a large number of works dealing with cranes, conveyers, etc.*

The electric lift was first introduced in America, and in that country has developed in a direction and to an extent to which we are hardly likely to go. We have, however, followed American practice so far as we have been able. In doing so, we no doubt follow the course of least resistance, but the time seems to have come when we should undertake investigation and research upon our own account, with a view to developing a lift more particularly applicable to our own requirements. The conditions in this country are totally different from those existing in America. Here we are restricted in our buildings to a capacity of 250 000 cubic feet, whereas in America there is no such restriction and buildings range in size up to those with 30 to 60 floors and a floor area of 40 acres. On the other hand we are delightfully free from "red tape" or restrictions of any sort in the design of our lift machinery; whereas in America, where the lift is so important a factor in the daily life of the citizen that it is calculated that in the big cities the lifts run more miles per day than the combined road car and underground services, it has been found necessary to impose restrictions and bye-laws which, whilst protecting the interests of the community, are nevertheless a deterrent to the progress of invention and design.

The reason that so little has been written on this subject is no doubt partly because an electric lift is a combination product in which the builder, the electrician and the engineer all take part under the general direction of the architect, and sometimes—too seldom—of the consulting engineer. There are a number of problems concerning the construction of electric lifts which, so far as I know, have not been investigated, and the solution of which would be of great interest and benefit to the industry. It may be that these problems have been dealt with by individual manufacturers, in which case I hope that this paper will be an incentive to publication.

A fundamental problem is that of definition. Owing to the lack of other literature, one in search of information must refer to makers' catalogues and is at once confronted with a confusion of terms, sometimes used to designate the same thing and sometimes employed by certain makers to differentiate between different things.

* Since this paper was drafted a comprehensive work entitled "Electric Lift Equipment for Modern Buildings" by Ronald Grierson has been published by Messrs. Chapman & Hall.

Thus the terms "Vee" wheel drive, sheave drive, traction drive, friction drive, and half-wrap drive, are all used to designate the same thing. Lift, hoist and elevator are interchangeable terms, as are also service lift and goods lift. I suggest that it would be useful for lift makers to get together and adopt a code of definitions.

An electric lift consists essentially of:—

(1) A car or platform suitably designed to transport the required load.
(2) Guides, usually of wood or steel, rigidly attached to the building structure.
(3) Guide shoes attached to the car or platform so as to engage the guides.
(4) A counterweight.
(5) A rope or chain by which the car or platform and counterweight are suspended and which transmits motion from the driving engine.
(6) A driving sheave or drum with which the rope or chain engages.
(7) Gearing (usually worm and wheel) by which power is transmitted from the electric motor to the driving sheave or drum.
(8) An electric motor.
(9) An electromagnetic brake, usually operating upon a drum constructed in one with the coupling between the motor and worm shaft.
(10) A controller designed to start and stop the motor by means of suitable provision in the car or on one or more landings.
(11) Safety devices which may be simple or complex according to the circumstances and are intended to render accident impossible from the failure of any part of the lift or supply, or from the opening of a landing gate when the car is absent.

The cost of electric lift service comprises interest and sinking fund upon capital expenditure, rent, insurance, maintenance and renewals, energy and attendance. These factors of ultimate cost should be weighed before deciding upon the preliminary specification for any particular lift installation. It follows, then, that this consideration should be given before any scheme has gone so far as to impose limitations upon any of the factors. It also follows that where the architect takes the sole responsibility for the preliminary specification, very great care is required in comparing and examining tenders, as no two makers ever offer quite the same thing. An electric lift is too complicated a piece of machinery to admit of two makers quoting for the same equipment, unless to a very detailed specification such as can only be prepared by a lift engineer, and such important factors as maintenance costs, energy consumption and attendance are greatly affected by the details of the design offered. The actual service given by lifts built to the same general specification and designed to run at the same speed under the same general conditions will also vary considerably, and the number of trips which will be completed and passengers carried in a day by a lift acting upon a smooth and rapid acceleration curve, with accurate floor levelling, will be far greater than with a lift less carefully designed.

It is advisable, therefore, in all important new construction that the architect should, in the earliest stages of the project and before any building plans are settled, call in either a consultant specializing in lift engineering, or a manufacturer of experience. Such a consultant, after considering the size and purpose of the building, its situation, the position of entrances, etc., will be able to calculate the probable traffic and advise on the number, size and best position of the lifts required. He will also, upon the same basis of information, be able to advise upon the most economical scheme and the most suitable method of control.

Lift makers complain that they are not consulted until it is too late to influence the general specification, and therefore it often happens that two lifts are installed where one would be more suitable, or, conversely, that one large lift is installed where two smaller ones would give better service. The winding engine has frequently to be fitted in a position where it is impossible to get the best results, and the conditions are sometimes such that the rope-reeving is bad and the total cost of maintenance doubled as a result. Automatic push-button control is installed in places where car-switch control is essential, and expensive alterations have to be made after erection. Again, car-switch control is installed in places where automatic push-button control would be better and would save the cost of attendance.

A really efficient lift service serving the incoming and outgoing as well as the floor-to-floor traffic, is of far more importance than the staircase. Its location should be a primary consideration, and the staircase considered principally in relation to its effectiveness as a fire escape.

I have said that, given the necessary particulars of a building, the lift engineer will be able to calculate the probable traffic. It must be admitted, however, that the lift engineer himself does not usually employ any scientific method in arriving at the number of passengers per minute which will require lift service on each particular floor during the busy part of the day. Each will draw upon his own experience and home-made formulæ. If these could be collated, the general advantage would be served and many mistakes avoided.

Some interesting figures derived from American practice are given in a paper* by Mr. Harrison P. Reed, from which we learn that in New York City from 65 to 100 sq. ft. of rentable floor space is the average allowance per person occupying an office building. In other cities the allowance should be increased to 150 sq. ft. per person, and it is estimated that a lift service should be provided to empty such buildings above the first floor in from 40 to 60 minutes. It is, however, doubtful if American figures of this description apply to this country. The only English pronouncement that I can find is contained in a paper read recently by Mr. C. H. J. Day before the Association of Engineers-in-Charge, in which he says—referring to a large office building—that the average density of population is about 120 sq. ft. of floor space for each occupant, but

* "Electric Power Applications to Passenger and Freight Elevators," *Transactions of the American Institute of Electrical Engineers*, 1900, vol. 41, p. 325.

when one or two large firms occupy a whole building the population is almost certain to be denser than this, amounting perhaps to as much as 80 sq. ft. of floor space per person.

In the absence of any definite information on this point, Mr. Day says that it is considered safe to assume about 110 sq. ft. per person as a fair average. He also says that in buildings where tests have been made, the rate of traffic flow at the busiest time of the day has been found to be such as to include the equivalent of the entire population of the building in 45 minutes, and that the passenger traffic can be predetermined by allowing for a period of rush from 15 to 20 minutes, during which time a number equal to one-third of the population of the building is dealt with.

Figures derived from my own observation are not in agreement with this, but I must confess that although I have been investigating the subject for some considerable time I have not yet amassed sufficient data to

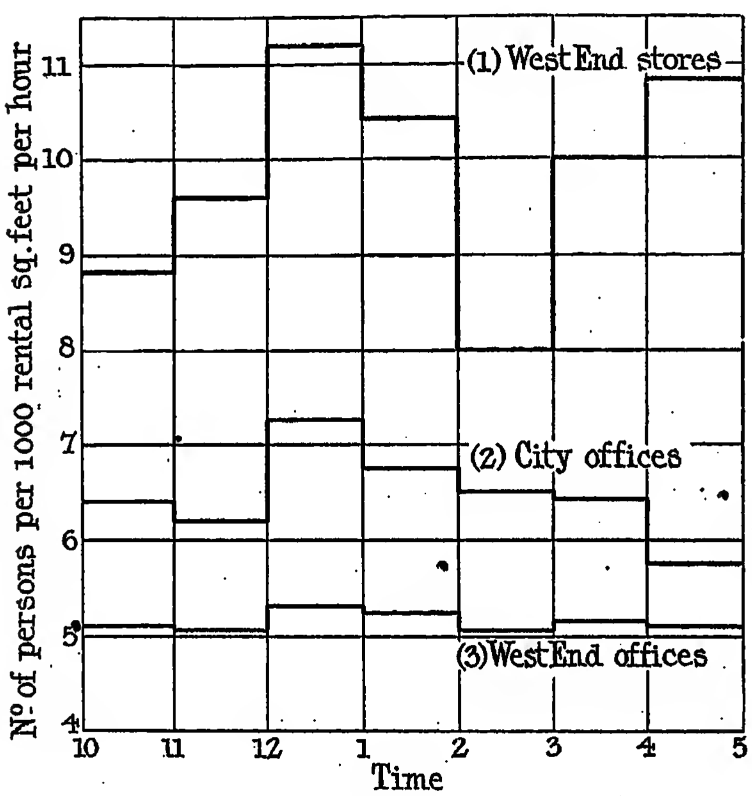


FIG. 1.

permit of my making an authoritative pronouncement. The means adopted in this investigation may be of interest and may possibly lead to the suggestion of better methods in the course of discussion.

In the first place the buildings in which lifts are usually installed have been divided into a large number of classes and each class has been separately examined under conditions which, I believe, apply to that particular class. For instance, in large drapery establishments and multiple-store buildings I count the number of persons per minute proceeding from the ground floor to upper floors. In office buildings of the class usually sub-let to a large number of different tenants I take no notice of persons arriving at or departing from the basement, ground floor or first floor, but make the count upon the second floor, of all persons arriving at, passing, or departing from that floor. In office buildings in which several or all the floors are occupied by the same tenant—an insurance office, for instance—I count the number of persons arriving at and departing from each floor, so as to check the inter-floor traffic; and in buildings where there is a restaurant on one of the floors a separate census is taken of the number of persons arriving at and departing from the restaurant, in order to check the special traffic so created. In taking this census of traffic in existing occupied buildings, I have at the outset been faced with the fact that existing lift accommodation is, in almost every instance, insufficient. It has been necessary, therefore, to count not only persons using the lifts but also those using the staircases.

For the present I will confine myself to a few examples to indicate the nature of the results obtained. In each case the figures have been reduced to per 1 000 sq. ft. of rental floor space served by the lifts.

In Fig. 1, curve (1) represents the average traffic counted in a group of West End drapery establishments. In each case the number of persons proceeding per hour from the ground floor to any other floor has been counted, and the curve represents the average of all establishments examined. Curve (2) represents a similar average deduced from a count taken in a large group of city office buildings of the class in which the floors are sub-let to a variety of tenants. The

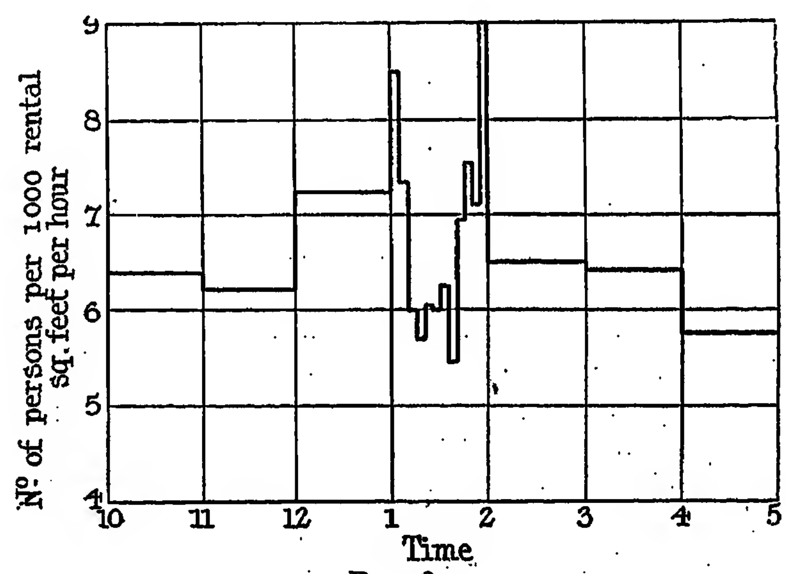


FIG. 2.

curve indicates the number of persons per hour who arrive at or pass the second floor. In order to obtain a more accurate estimate of the period between 1 o'clock and 2 o'clock mid-day, the more detailed curve shown in Fig. 2 was prepared. The third example in Fig. 1 comprises a similar group of offices situated in the West End of London. The different characteristics are strikingly shown. In this case there is no "rush" period, so that, in order to provide the same lift facilities for the same population, less lift capacity is required.

To arrive with more accuracy at the lift capacity required for a city (London) office building of the class usually sub-let to a variety of tenants, we refer again to Fig. 1, from which it will be observed that the largest amount of traffic occurs between noon and 1 p.m. As the effect of the dinner-hour traffic is not clearly indicated, it was decided to take detailed obser-

vations over the whole period from 11.30 a.m. to 2.30 p.m., in order to arrive at the true maximum traffic requirements on the building.

Eleven office blocks comprising both large and small buildings were selected. In every case care was taken to watch not only all lifts but all staircases simultaneously. A count was made upon the second floor of every person arriving at, departing from, or passing that floor in each direction. The result of this count has been carefully reduced to persons per hour per 1 000 sq. ft. of rental floor area above the first floor. The observations were recorded at the end of every minute, and plotted for each separate building in the series of curves shown, the average of which is given in Fig. 3. Some interesting things may be learnt from this figure. It will be noticed at once that the traffic is inclined to move in bunches, and that had the observations been taken over 2-minute intervals the curve would have been very different in form. A curve has been prepared to illustrate this, and shows clearly the errors likely to arise from taking a count gauged by reference to Table 1, which gives figures for city (London) office buildings.

TABLE 1.

Lift capacity in persons per hour per 1 000 sq. ft. rental floor area above first floor	Number of minutes during the day when lift capacity will be insufficient
7	84
7·5	56
8	33
8·5	14
9	5
9·5	1

Assuming that we allow for a lift capacity of 9·6 persons per hour per 1 000 sq. ft. of rental floor area above the first floor in the class of building specified, and taking the New York allowance of 65 to 100 sq. ft.

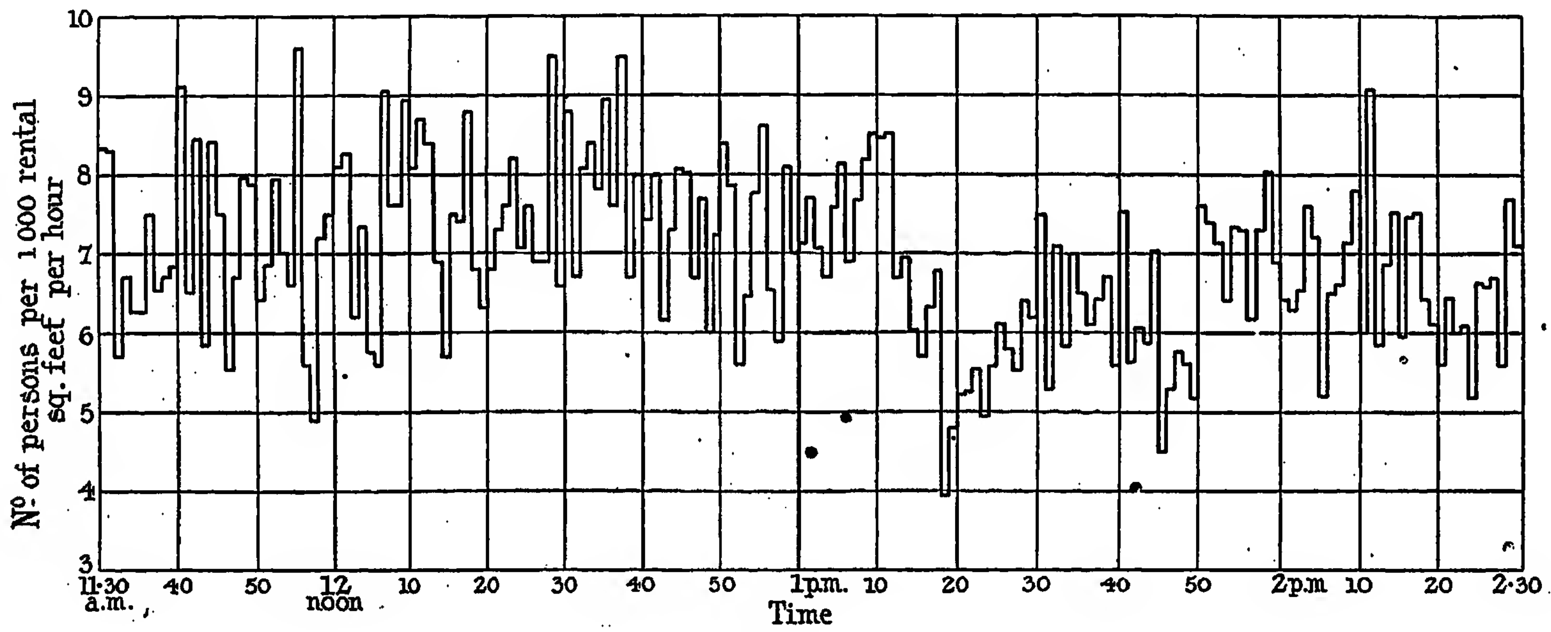


FIG. 3.

over any period longer than 1 minute, as it is the maximum traffic and not the average with which the lift engineer has to deal.

Referring to Fig. 3 we find that the average traffic per hour per unit of floor space taken during the period 11.30 a.m. to 2.30 p.m. is approximately 6·98, and between 12.10 p.m. and 1.10 p.m., 7·5. If, however, provision is made for the average traffic only, it is obvious that many people will either wait for several minutes for lift service or use the stairs in preference.

It may be considered unnecessary to provide accommodation calculated upon a maximum traffic which may only occur during a single minute of the day, but in this connection it must be remembered that this curve itself is an average of 11 typical buildings and that the maximum of 9·6 must be compared with the maximum of over 20, shown for a 1-minute period on three of the individual buildings. It is reasonable, therefore, to provide for the maximum indicated in Fig. 3.

The effect of providing a lesser lift service may be of rental floor space per inhabitant—say 82·5 sq. ft. —the lift capacity at which we have arrived would allow for the emptying of the building above the first floor in 1 hr. 15 min., a figure which, it will be noted, differs altogether from those arrived at by American authorities and by Mr. Day, but which is, I believe, when applied to buildings in the City of London, a more accurate one.

In order, then, to discover the lift capacity in such a building, the following formula may be used:—

$$\frac{9 \cdot 6 A}{NL}$$

where A = thousands of sq. ft. rental floor area above the first floor;

N = number of circular trips, including stoppages, which can be made per lift per hour; and

L = number of lifts.

Having discovered the total lift capacity required, it is next necessary to decide the number of lifts to be employed and their speed.

As about 30 seconds represents the limit of patience to be expected of the average city man waiting for a lift, a building cannot be considered to be adequately served when the occupants or visitors are asked to wait longer. To calculate the number of lifts required to handle a given traffic and give a half-minute service, the overall speed of the lifts—allowing for all stoppages—must be known. The number of stoppages a lift may be required to make in the course of a return journey from the ground floor and back again varies considerably, but in the class of building which we have been considering, it is found to average about one stop for every 42 ft. of running. Allowing 12 seconds per stop for loss in acceleration, deceleration, opening and closing of gates and for the time taken by the passengers in entering and leaving the car, together with a further allowance to cover general loss of time, we find that the overall time in seconds required for the circular trip will be :—

$$\frac{60 \times 2T}{R} + \frac{2T \times 12}{42}$$

where R = running speed of lift in ft. per min.,
T = total travel of lift in feet in one direction.

In the case of a lift with 100 ft. travel and a running speed of 200 ft. per min., the overall time for the circular journey will be 117 seconds. In such a city office building two lifts of given capacity might not provide the required service, whereas three would more than do so, but by slightly increasing the speed the two lifts would suffice.

It will be observed that I make an allowance of 12 seconds for stoppage and lost time in an all-round average service. This will only be found sufficient provided the car is not too large. If the capacity is more than 10 persons—including attendant—the time allowance and the total lift capacity must be increased accordingly. It must also be assumed that the lifts are suitably situated and designed with wide openings for the easy ingress and egress of passengers. Under such conditions the effect of running speed upon overall speed may be set out as in Table 2 for a lift of 100 ft. travel.

TABLE 2.

Running speed	Overall time per circular trip with 100 ft. travel
ft. per min.	secs.
100	177
200	117
300	97
400	87
500	81
600	77

It will be observed that the saving in overall running time falls off as the running speed is increased, so there must come a point at which additional capital cost is not justified by the saving in time. In Table 3, approximate figures are given in order to indicate the relation of running speed to capital cost for a lift designed for a load of 10 persons.

TABLE 3.

Running speed	Extra cost (approx.) of machinery and safety devices (July 1923)
ft. per min.	£
60	—
100	25
200	75
400	150
500	190
600	220

The figures do not represent a large percentage upon the cost of a lift of the travel and capacity we have been considering, and, when taken in conjunction with a consideration of the saving of rent and attendance, will generally work out in favour of the higher-speed lift.

It has been maintained that lifts of a speed of over 250 ft. per min. cannot be justified in this country because of the lesser height of our buildings as compared with those in America, and that the period of acceleration and deceleration occupies practically the whole time of the short average journey, so that there is no opportunity for the lift to run at its full designed speed. The objection is a sound one and is supported by the practice of making the acceleration and deceleration periods long, in the belief that it is necessary to do so if the internal economy of passengers is not to be upset. Nevertheless, as ground space is of so great a value in large cities the importance of designing a lift which will accelerate and decelerate quickly, and so permit advantage to be taken of higher speeds, will be appreciated.

In order to investigate the effect of various forms of lift acceleration upon the average passenger, I have made a large number of experiments. The earlier efforts were very crude, the apparatus consisting of weights suspended upon springs, on the spring-balance principle, and arranged to record their motion upon a paper chart, the passengers at the same time being asked to note their physical sensations. With this apparatus it was discovered that the critical period of acceleration was too brief to be dealt with scientifically in this way. The next step was to devise an electrical method of recording what happened, and with the help of the Cambridge and Paul Scientific Instrument Co., and particularly of Mr. R. S. Whipple and Mr. Barron of that company, the following arrangement was adopted :—

A series of coils of copper wire are wound on the outside of a tube 6 ft. long and about 3 in. in diameter. These coils, which are spaced 2 in. apart and connected in series, are in circuit with a small string galvanometer,

a feature of which is its short period of vibration. An image of the string of this galvanometer is projected by means of a "Pointolite" lamp on to a moving photographic film. The tube is inserted at the bottom of the lift shaft in such a position that the car can pass freely without fouling. Carried from an arm at the top of the car is a cord to the end of which is attached a small cobalt-steel magnet, its position being such that as the lift travels up or down, the magnet is made to move inside the tube, thereby inducing an electromotive force in the coil windings and causing a deflection of the galvanometer string, the movements of which are recorded on the photographic film.

Accurate timing of the record is effected by a synchronous motor run from a tuning fork making 50 vibrations per second. This motor carries a disc, on the circumference of which are fitted five spokes, each being introduced in turn into the path of the beam of light. In this way the record is ruled with a series of lines, the space between any two of which represents 0·04 sec. The film speed employed is approximately 3 ft. per sec., rendering it possible to read the record to 0·002 sec. In the record illustrated, the passage of the magnet through each coil is indicated by a deflection of the string, and reference to the time scale makes it possible to determine the time taken for the lift to rise each successive 2 in. By plotting "time" against "inches rise of lift" information is obtained from which a true acceleration or deceleration curve may be produced. In Figs. 4 (*a*) and 4 (*b*) are reproduced specimens of the films produced in this way. These films illustrate different forms of acceleration on a passenger lift running at 360 ft. per min. It should be noted that the time intervals indicated by the vertical lines upon the films are accurately controlled by the tuning fork method as described, but the space intervals vary, as the result of variations in the film speed. A corresponding correction must be made in taking measurements from the films. This method has not, so far as I am aware, been used before for the purpose of obtaining such data.

From a study of these films we discover that the unpleasant sensations experienced by most passengers at the starting and stopping of a fast-running lift are due not so much to a too rapid acceleration as to a sharp change of acceleration, the result of imperfect control. The remedy is not an extension of the total period of acceleration, but a correction and smoothing out of the curve. Working upon these lines it is found possible to accelerate a lift to 300 ft. per min. within a space of 24 in., or to 600 ft. per min. in less than 48 in., without discomfort to the passengers, and to decelerate in a similar period. This means that the time lost in acceleration and deceleration of a lift at 300 ft. per min. with average runs of 42 ft. need not exceed 5 per cent of the running time, and at 600 ft. per min., 10 per cent, the number of seconds lost being the same in each case. It also means a saving in energy consumption.

Fig. 5 represents a series of time/distance curves taken upon the starting of a 15-cwt. passenger lift running at 360 ft. per min. in a building in Kingsway. The different results are obtained by varying the armature starting resistance and the rapidity of cutting out. No. 6 of this series of curves represents a condition of particularly comfortable starting, and I have chosen this curve to illustrate in Figs. 6 (*a*) and 6 (*b*) the derived velocity and acceleration curves.

In Fig. 6 (*a*) it will be observed that the lift attains a maximum velocity in 1·4 sec. In Fig. 6 (*b*) it will be noticed that the acceleration over the first fifth of a second is not plotted. This is because it has not been found possible to obtain accurate measurements from this part of the film. As more information about this part of the acceleration curve is of great importance, I am now arranging apparatus to investigate in detail what happens in this first fifth of a second. It will also be noted in Fig. 6 (*b*) that the acceleration proceeds in a series of periodic leaps. This is a feature of the whole of these records. At first the explanation seemed simple because in most instances there are eight clearly marked periods, and it so happens that on the normal controller usually experimented with there are eight batches of starting resistances in the armature circuit.

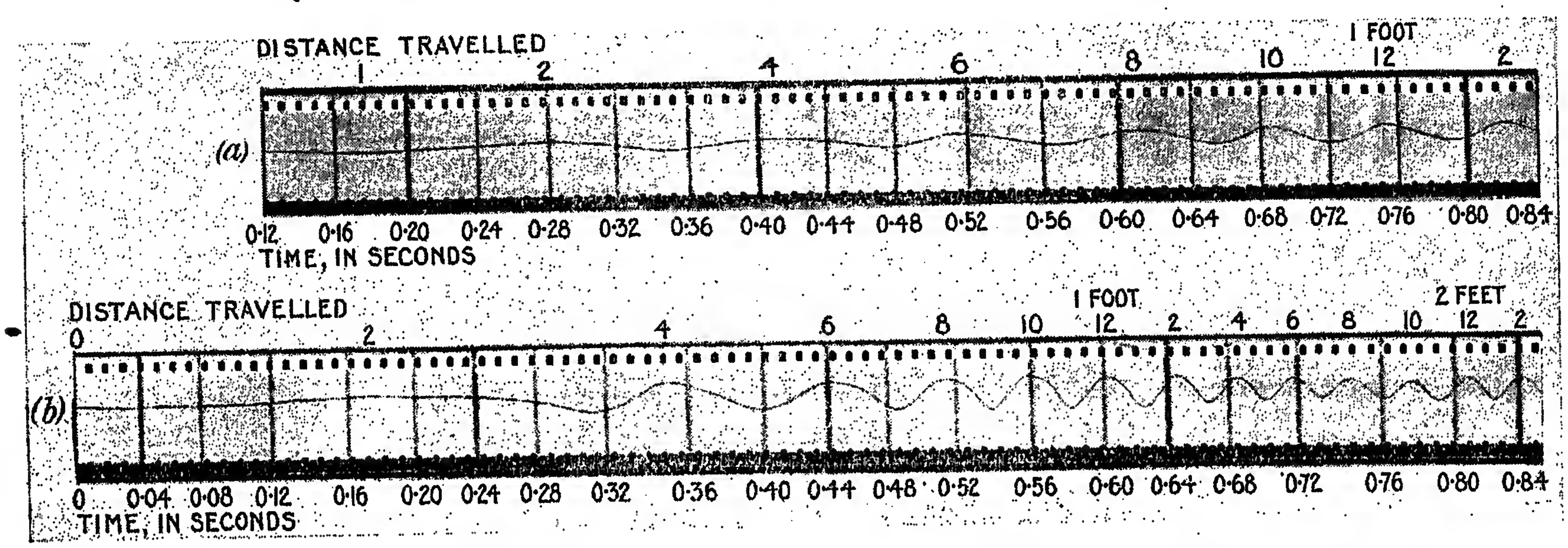


FIG. 4.—Reproduction of two films obtained in connection with

Further examination shows that although the starting contacts undoubtedly affect the shape of the curve they are not responsible for it. For instance, if the number of starting contacts is reduced, the number of periods shown on the acceleration curve is increased.

I am not as yet prepared to explain the cause of this periodic acceleration; perhaps some light will be thrown upon it during the discussion. The variety of the forms obtained and the fact that on repeating the same experiment the same form is repeated, seems to show that the shape is governed by various forces acting sometimes together and sometimes in opposition, depending upon the conditions of starting.

It may be noted, in reference to Fig. 6 (*b*), that the steps in acceleration indicated are too rapid to have any physical effect upon the passengers, for the purpose of considering which question an average curve should be drawn. In this sense the curve indicated in Fig. 6 (*b*) is a good one, provided that the unplotted part in the first fifth of a second does not descend from too great a height.

As a matter of interest I propose to show by means of lantern slides a few other examples of these curves. The first represents the acceleration of an hydraulic goods lift, and the next two represent, I think, a somewhat daring experiment, when a large passenger lift running at 400 ft. per min. and driven by a 21-h.p. motor was switched direct on to the main without any intermediate resistance. The first is taken under conditions of maximum load and the second with minimum load.

It will be observed from the figures given that the 600-ft.-per-min. lift will carry 26 per cent more passengers per hour than the 300-ft.-per-min. lift will do, or to carry the same number of passengers may be of 20 per cent less capacity. There is not, so far as I know, any lift running at 600 ft. per min. in this country, nor to my knowledge is there one running at over 400 ft. per min., but I am quite convinced that with the increasing site values in our cities there is opportunity for the economic use of higher speeds.

Having discovered the total capacity required in a certain building and decided upon the speed and capacity of each lift, the number of lifts required will follow as a matter of course.

Before passing on to the consideration of other lift problems, it is interesting to note here the experience of the London Electric Tube Railways, kindly given me by the Operation Manager, Mr. A. P. Thomas. The number of lifts installed in a tube station depends upon the volume of traffic, and is approximately:—

For 7 000 passengers per day—2 lifts.
For 10 000 passengers per day—3 lifts.
For 13 000 to 30 000 passengers per day—4 lifts.

The number is to a certain extent dependent upon the depth of the shaft. With a 4-lift equipment and a depth of shaft of 72 ft., a general average service of 2 mins. 18 secs. per lift can be observed, allowing

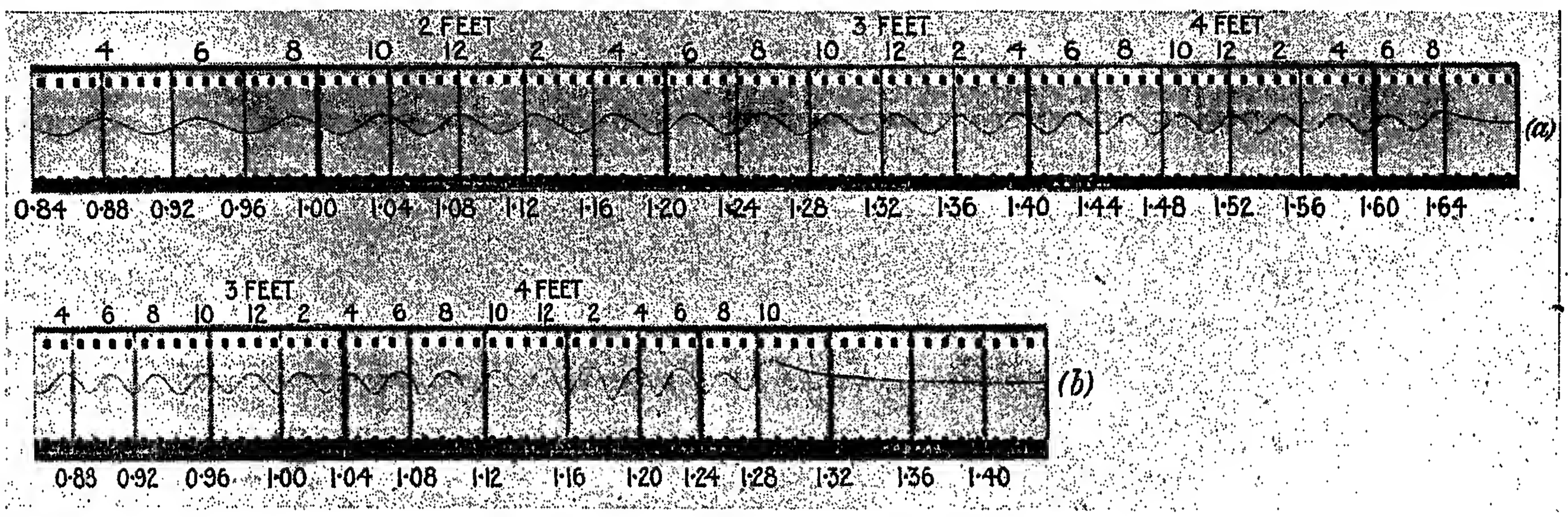
7½ secs. for preparing lift.
30 secs. for loading lift.
7½ secs. for starting lift.
24 secs. for running lift.
45 secs. for discharging lift.
24 secs. for running lift.

Or a total of 138 secs. for the round trip, or 26 trips per hour.

The speeds of the lifts on the London Electric Railways are about 180 ft. per min., except at Hampstead, where the shaft is deeper than that at any other station, viz. 181 ft. There the speed is 200 ft. per min.

There is a tendency to increase the speed of tube railway lifts to meet the desire of the travelling public for faster travel. A lift service, however well run, compares unfavourably with an escalator service, and lifts have been replaced by escalators at a number of stations. No lifts at all are provided on the new stations north of Edgware-road, a convenient escalator system having been introduced. For all shafts of a depth of 60 ft. and under, the escalator provides a better means of transport, but for a shaft above this depth high-speed lifts are desirable.

The winding engine giving motion to the ropes may be fitted with a drum to which the car and counterweight



acceleration tests on a passenger lift having a running speed of 360 feet per minute.

ropes are positively attached, or with a V-groove sheave transmitting motion to the ropes by friction, as a pulley does to a belt. Had I been reading this paper 20 to 25 years ago I should at this point no doubt have entered upon a strong advocacy of the sheave drive, but this is no longer necessary, as most makers have now adopted this arrangement.

Serious danger attaches to the drum method of driving, inasmuch as in the event of overrunning and the failure of safety devices the positively driven ropes will cause either the car or the counterweight to crash. With sheave driving the effect of overrunning and failure of the safety devices is to land the car or counterweight upon the final stops at the foot of the well, and with the ropes thus relieved of load the gear can continue to revolve until the ropes are worn through, which will take many hours—or days.

The cost of maintenance of an electric passenger lift in business premises varies from about £20 to £100 per annum, and is largely affected by the frequency of re-roping. The cost of re-roping is largely made up of labour and is often augmented by the necessity for overtime work, but, apart from the actual cost of the ropes and work, a further loss must be taken into consideration in respect of the discontinuance of lift service whilst the work is in progress.

A prime consideration in the selection of a lift should therefore be the ultimate maintenance cost, with particular regard to re-roping, and to accept tenders for lifts without this consideration is to place a premium on inefficiency.

Frequently the breaking strain of the ropes to be employed on a new lift is specified without regard to the fact, supported by lift engineers having long experience of maintenance, that a rope of less tensile strength, of the super-ductile class, will in many cases give better results over a number of years. If such ropes are to be employed, care must be taken in the first instance that the lower breaking strain is compensated by larger, or additional, ropes, to provide the necessary factor of safety.

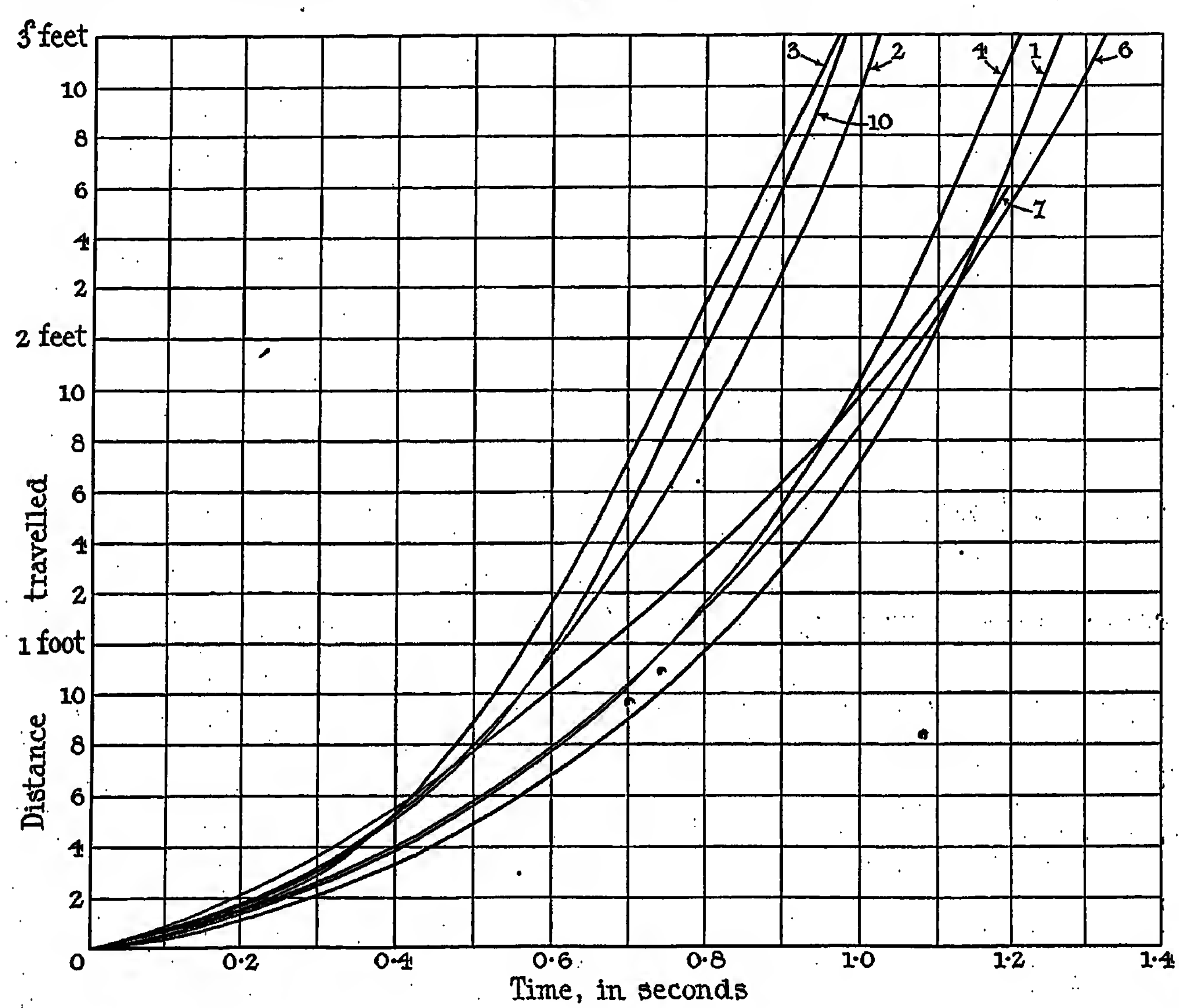


Fig. 5.

Both lift and rope makers differ in their advice as to the most suitable rope for use in any particular case. My own experience suggests the use of a super-ductile steel for ropes which fail on account of damage by bending, and a hard steel of high tensile strength for lifts on which the ropes fail from the frictional wear due to slip between the ropes and the driving sheave.

A most important factor affecting the life of ropes is the method of reeving employed. The option to select the best method is often taken out of the hands of the lift maker by the architect, who advances his plans too far before the details of the lifts are considered, and imposes hampering restrictions.

In Fig. 7 are shown diagrammatically the methods of reeving more usually employed, in (*a*), (*b*), (*c*) and (*d*)

the winding engine being indicated at the head of the well, and in (*e*), (*f*), (*g*) and (*h*) at the foot.

The ideal arrangement is indicated in (*a*), in which the driving sheave spans the distance between the suspension points of the car and counterweight. Arrangement (*b*) is not so satisfactory but may be necessitated by considerations of economy, because the smaller the diameter of the driving sheave the less expensive are the motor and gear, or because the distance between the car and counterweight centres is too great to be conveniently spanned by a single sheave, or in order to comply with the particular building plan. Arrangement (*c*)—sometimes termed the "full-wrap drive"—may be employed where the out-of-balance load is considerable and there is danger of rope slip on the driving sheave. It is possible with this method of reeving to employ U grooves instead of the usual V grooves on the driving sheave, thereby greatly reducing the wear on the ropes. With this arrangement the idler sheave may be so placed [as in (*b*)] as to act as a diverting sheave in cases where the driving sheave cannot be designed to span the distance between the car and counterweight. Arrangement (*d*) shows an adaptation of reeving which may be applied to (*a*), (*b*) or (*c*), introducing a 2 : 1 reduction in car speed. This method and further extension of the same principle may be conveniently employed when very heavy loads have to be raised at low speed. It will be noticed that in this diagram is introduced for the first time an S or backward bend in the rope. Such bends should be avoided where possible as they are much more destructive than a series of bends in the same direction.

Diagrams (*e*), (*f*), (*g*) and (*h*) show similar arrangements but with the winding engine at the foot of the well. In these arrangements the lengths of the ropes are greatly increased and S bends are introduced in every instance. The arrangement with diverting sheave shown in (*f*) is for some reason, which I am not prepared to explain, exceptionally destructive of the ropes.

Whatever system of reeving is employed, the larger the diameter of the sheaves used the longer will be the life of the ropes. In these diagrams only one rope is indicated, but it must be understood that in passenger-lift practice from four to six or more ropes running side by side are employed.

It will be seen that the winding engine may be placed at the head of the well directly over the work, at the foot, or on any of the intermediate floors. The advantages claimed for placing the gear at the foot of the well are:—

(1) Greater accessibility;
(2) Greater rigidity and therefore longer life;
(3) Less likelihood of nuisance due to noise and vibration.

In practice I find these advantages largely non-existent, whereas the obvious disadvantage of employing ropes of at least treble the length is very evident. Not only is the cost of ropes and of re-roping increased on account of this greater length, but the wear of the ropes is also increased by the larger number of bends—often S bends—which the ropes must make.

It is true that under certain circumstances the wear on the ropes can be reduced by so arranging the position of the winding engine that that part of the ropes which passes over the driving sheave does not also pass over the top sheaves—and vice versa; but even where this is done, unless diverting sheaves can be eliminated, the wear is greater than with the plain see-saw arrangement with the winding engine at the top.

The increased cost of maintenance due to a bad roping scheme may easily be sufficient to justify a capital expenditure of several hundreds of pounds in the first place, and may be avoided altogether if proper provision is made in the original plans.

One objection which architects and builders occasionally advance to the placing of the winding engine at the top of the building, is the increased weight on the upper structure. Examination will show that there is nothing in this argument except in the very unusual event of the winding engine weighing more than the combined weight of the car, load and counterweight. Under all other conditions the strain upon the upper structure is greater if the winding engine is located below.

For low-speed lifts, such as are usual in this country, it is essential to interpose some form of gearing between the motor and the driving sheave. Many types of gearing have been tried, but the worm and wheel is almost universally employed because of its many advantages for this particular work. Worm gearing is conveniently built to give precisely the ratios required by the lift engineer, and can be readily designed with a suitable angle of lead to render the gear self-sustaining; that is to say, so that it shall not be possible for the load or counterweight to set the lift in motion by driving the motor back through the gear. This provision requires the efficiency of the gear to be no more than 50 per cent, but the value of this additional safety factor is so great that the loss of efficiency is willingly sacrificed in order to secure it.

Figs. 8 and 9 show two typical arrangements of winding engine, comprising motor, worm gear, brake and sheave. The fundamental difference lies in the arrangement of the worm gear. In Fig. 8 the worm is located above the wheel, whereas in Fig. 9 it is below the wheel. I do not know that the comparative advantages of these types for this purpose have ever been discussed, and lift makers are divided in their opinion and recommendation. To the casual observer I think it will appear at once that the over-worm type is the sounder engineering job. With this arrangement the low-speed main shaft—that carrying the whole of the weight—is placed low down upon the bedplate in the most favourable position. The main part of the bedplate is hollow and forms an ample receptacle for oil, with easy access for cleaning out the bottom of the gear-case so formed.

The advantages advanced by advocates of the under-worm type are, first, that the lubrication is more perfect, and secondly, that any wear taking place in the main shaft bearings allows the gears to drop closer into mesh instead of drawing the worm and wheel apart. On the question of lubrication it is true that with the over-worm type gear the worm is not running immersed in oil, but oil more than sufficient to provide ample lubrica-

tion is brought up by the hollow teeth of the wheel. If the inspection cover of such a gear be inadvertently removed whilst the gear is running, it will quickly be replaced to staunch the flood of oil which is thrown by centrifugal force from the worm. The gear case is so designed that this oil thrown from the worm is collected in gutters and conveyed to the worm and main shaft bearings, whence it finds its way back into the reservoir, which is kept filled to a height some inches above the teeth of the wheel. With this type of gear the main shaft bearings, which are the most important in the whole machine, are subjected to a continuous flow of oil passing through them. The answer to the second point is that if the main shaft bearings wear so much as to make an appreciable difference in the mesh of the gear it is time for these bearings to be

the intervention of gear may be employed. In this case the motor must, of course, be of very low speed and correspondingly expensive, and, as the self-sustaining feature of the worm gear is lost, additional precautions must be taken against accident.

Two methods of control are in use with modern electric passenger lifts; these may be referred to briefly as the "push-button" and the "car switch." The push-button method is automatic; that is to say the car stops automatically at the floor desired and the lift can be operated by the passenger without the assistance of a lift attendant. The car-switch method requires the employment of a lift attendant and some skill to ensure stopping at floor-level.

The push-button lift is the more expensive, but the difference in cost is far more than justified by the

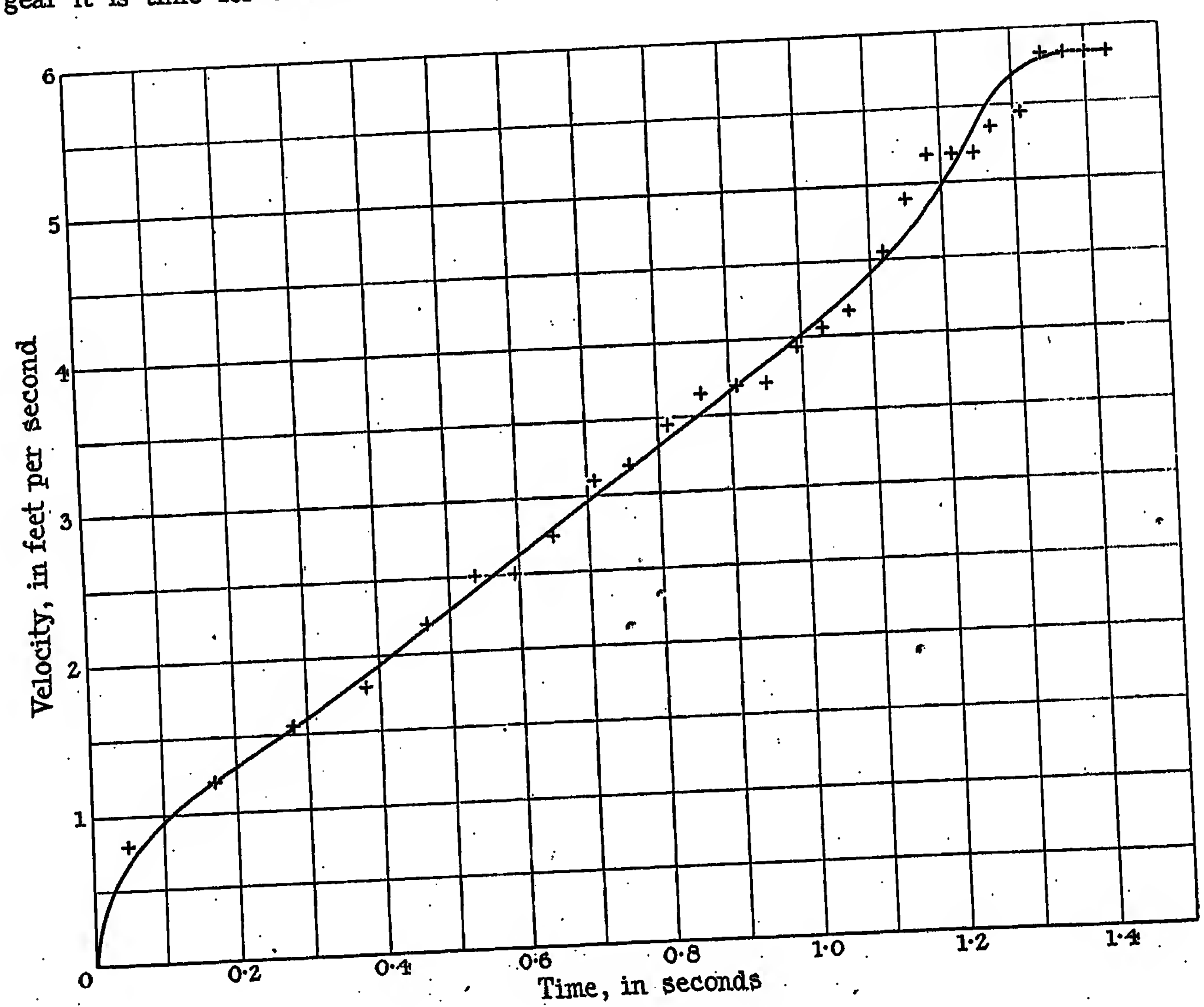


Fig. 6 (*a*).

re-bushed. To meet extreme cases, where no backlash of any sort is permissible between the worm and the wheel (these cases do not, in fact, concern lifts, but occur in certain pumping problems), a device of wedges below the main shaft bearings is introduced by means of which very fine adjustment of mesh can be obtained.

It will be observed that the over-worm type of gear that I am advocating is the more expensive, and, if it has the superiority I claim, deserves a due allowance in the consideration of competitive tenders.

For high-speed lifts such as I have advocated in the earlier part of this paper, the American practice of coupling the driving sheave direct to the motor without

saving in the cost of attendance. Its capacity is, however, far less than that of a car-switch lift of the same size, because there is some difficulty in employing a higher speed than 150 or 200 ft. per min. with an automatic lift, and because a single passenger on entering the car obtains complete control over the lift until he has completed his journey, although there may be many passengers waiting at intermediate floors. The automatic lift is therefore only suitable for places where the traffic is never so dense as to require the full capacity of the lift for many minutes at a time. The scope of the automatic lift might be considerably extended by the introduction of a satisfactory self-closing gate

to overcome the annoyance of the lift being thrown out of action by some careless passenger forgetting to close the gate after him, and by the incorporation of a suitable floor-levelling device which would permit of a higher running speed being employed. Lift makers are engaged upon these problems, so that there is a possibility of some advance being made in the direction of increasing the capacity of automatic lifts.

Automatic control lends itself to many variations in detail, but the general principle is much the same in all cases. One push-button is fixed at each landing gate and this will call the car to that landing, provided affecting the direction of rotation of the motor; also a solenoid the function of which is to overcome the force of the springs holding the brakes in position; and finally a solenoid operating the motor-starting rheostat. The particular solenoid which comes into operation in connection with the change-over direction switch depends upon the position of the car in the well at the time, so that if the car is at the foot of the well and the button for the first floor be pressed and the direction of rotation is found to be clockwise, then if the car is at the fifth floor and the same button is pressed the direction of rotation will be counter-clockwise.

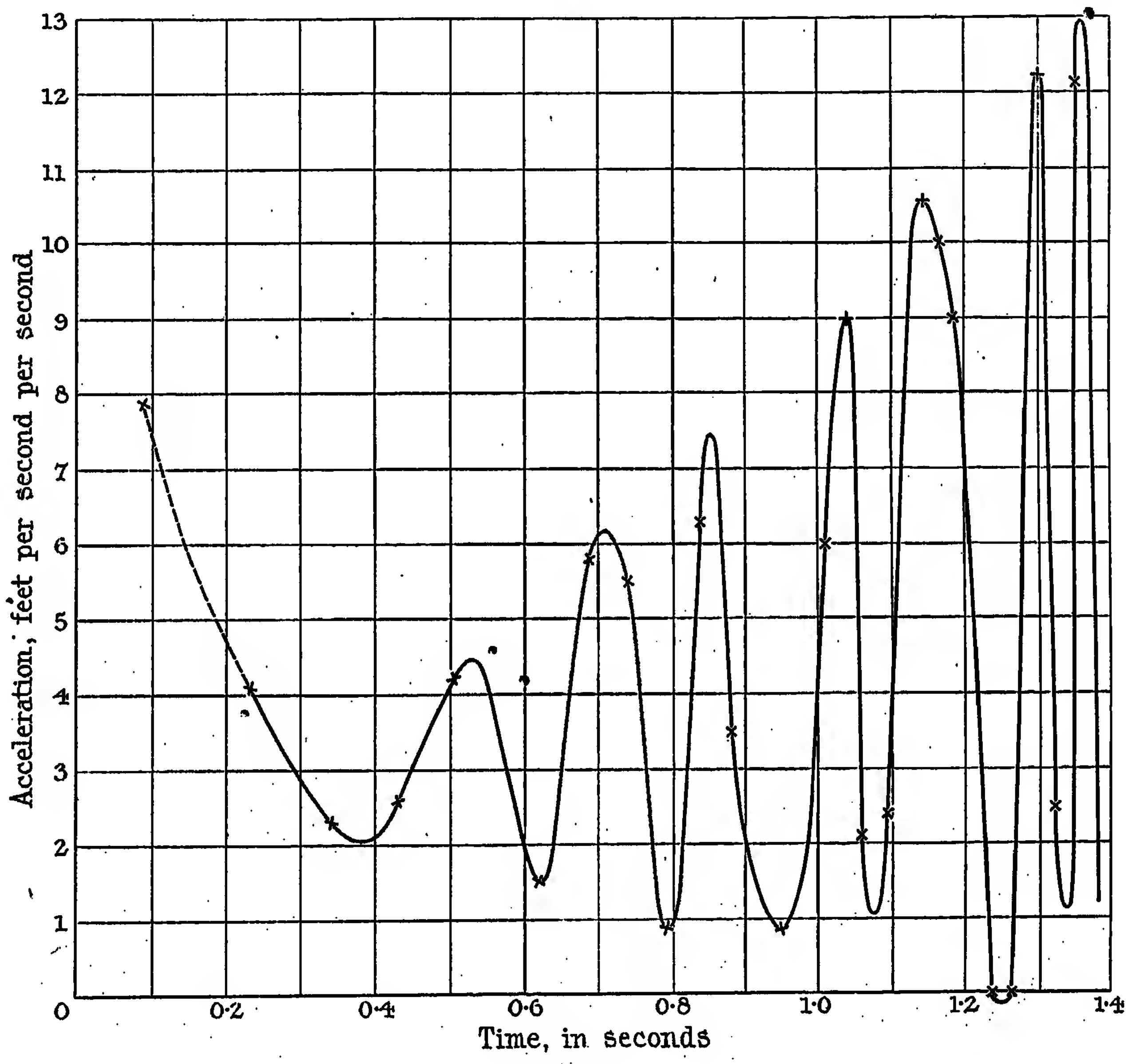


FIG. 6 (b).

it is at the moment disengaged and that all other landing gates are closed. A series of buttons fixed upon a tablet in the car—one button corresponding to each floor served—enables the car to be directed to any particular floor by pressing the corresponding button. On arrival at that floor the car will stop automatically. In a typical arrangement the push-buttons are connected to a series of relays representing each floor, by means of a circuit which is completed through contacts attached to each gate, so that when a button is pressed—subject to all gates being closed—the particular floor relay will operate. This relay closes the circuit of one or other of two coils operating a change-over solenoid switch

With car-switch control the connections are simpler, inasmuch as the push-button circuit and relays are omitted, the connections from the car switch being made direct to the solenoid direction switch. The diagram of connections of the control panel with which I am more particularly acquainted is given in Fig. 10. The same panel is used in connection with either the push-button or car-switch method of control. With this controller the shunt field of the motor is always left connected across the armature when the main current is disconnected. This arrangement entirely eliminates failure due to inductive discharge on opening the field circuit, and another valuable feature is that the

controller is of the double-pole type, the main source of supply being switched on and off at both poles at each operation of the lift. This eliminates a most insidious form of fault inherent in almost every other form of controller, in which an earth developing on one or other part of the control system may under certain circumstances allow of uncontrolled movement of the car.

As illustrating the service which these controllers are sometimes called upon to perform, a count was recently made in a drapery establishment in Oxford-street, London, in which two lifts each performed an average of 2 000 journeys per day. In making these tests great care was taken to eliminate any possibility of error. The motor rooms were kept locked, and accurate instruments were employed for counting and registering

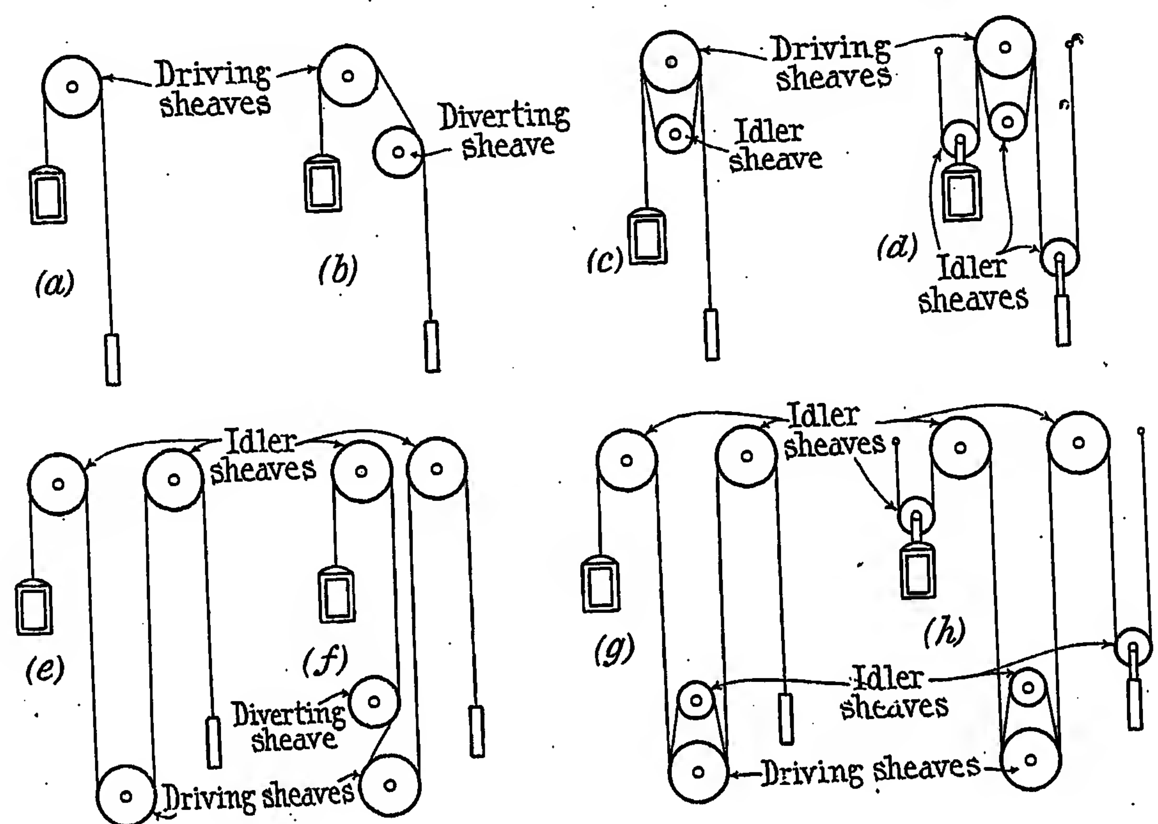


FIG. 7.

the work done. Independent observers were employed to check the results. During the whole month the only stoppage that occurred was one of 10 minutes upon one of the lifts to replace a car-switch contact.

It may be claimed, then, that electric lift controller designs have attained a high state of reliability. The most promising line for further advancement would

A very useful form of control, and one not sufficiently employed, consists of a combination of the push-button and car switch with a change-over device, so that during busy periods the lift may be car-switch operated at high speed by an attendant, and during slack periods push-button operated at a lower speed by the passengers.

The essentials of a good lift controller are that it shall start and accelerate the lift in the minimum of time consistent with the comfort of passengers, and

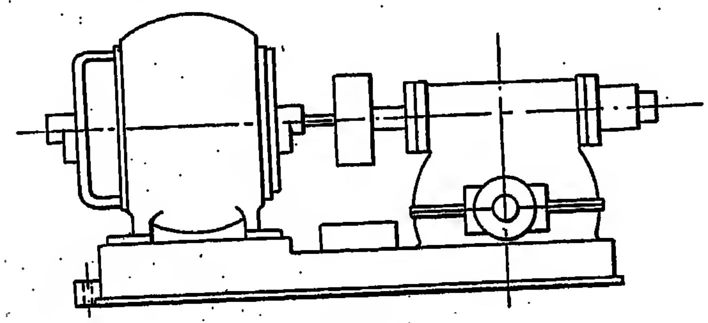


FIG. 8.

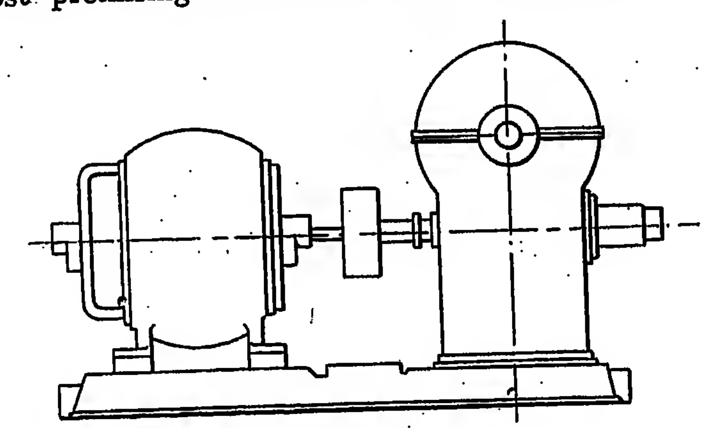


FIG. 9.

decelerate and stop in like manner, at the will of the operator. It must be reliable for a service sometimes extending to thousands of operations per day, and must be thoroughly robust and so constructed that a replacement or adjustment can be made readily without the possibility of upsetting the accuracy of its action. For many positions also it is often desirable that the controller should be silent in its operation.

seem to be in the direction of deceleration control, especially in conjunction with automatic lifts, thus permitting higher running speeds to be employed.

The energy consumption of an electric lift is principally dependent upon the number of times the lift is set into motion. The current required to accelerate the moving parts is far greater than that necessary to maintain the lift running, and very little,

if any, of this current is returned to the line during deceleration.

It follows, then, that with a car-switch lift the energy consumption depends very largely upon the skill of the operator in stopping the lift at floor-level. If he finds it necessary to "inch" at each stop, the energy consumption is enormously increased. This must always be the case when a new or an unskilful operator is employed. The higher the running speed of the lift the more likely is this loss to occur, owing to the increased difficulty of gauging floor-level.

Each lift maker has developed one or more devices to overcome this difficulty, but the fact that various makers recommend various solutions is in itself indicative that finality is not reached. Two-speed or three-speed control is sometimes made use of, the connections being brought back to the car switch, upon which two or

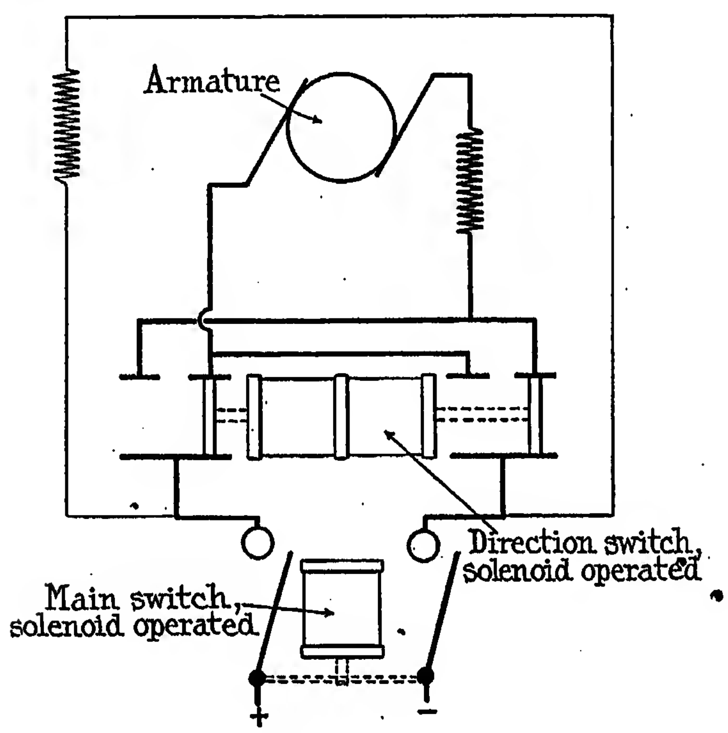


FIG. 10.

three stops in each direction are provided. Messrs. Waygood-Otis have introduced a device termed the "micro-drive" which not only attains the end in view but also maintains the car at the exact floor-level irrespective of the stretching of ropes or any other circumstance. That is to say, the lift having stopped at a particular floor, a heavy load wheeled into it may cause the car to sink—say half an inch—then the micro-drive machine will at once get into action and raise the car that half-inch. Mr. C. H. J. Day, in describing the micro-drive lift before the Association of Engineers-in-Charge, stated that it embodies two essential parts, the main hoisting machine and the micro-attachment.

The main hoisting machine, with the exception of the magnetic brake, involves no special features. The main brake is usually of the regular shoe type, except that the housing or frame, instead of being bolted to the bedplate, is fastened to the worm-wheel shaft of the micro-gear and revolves with it. This main brake performs a double function; first, with the micro-gear at rest it acts as a brake to stop the main machine, and secondly, when the micro-gear operates, it acts as a friction clutch driving the main machine. The micro-gear is in itself a small machine consisting of a motor, brake, and worm-gear reduction.

With the micro-levelling machine two controllers are combined in one, one to control the operation of the main motor and the other to control the operation of the micro-motor. The main controller is operated in the usual manner, i.e. by push-button, car-switch or mechanical control. The micro-controller is operated by a levelling switch mounted on the car frame. This levelling switch consists of two sets of contacts which control the micro-motor, one for the up and the other for the down direction. These contacts are operated by stationary cams in the lift shaft, there being two cams at each landing, one of which operates the up contacts and the other the down contacts. As the car approaches the floor at which it is intended to stop, the circuit of the main motor is interrupted, either automatically in the case of push-button control or by the car-switch or mechanically-operated mechanism.

If the main machine brings the car or platform above or below the desired floor-level the levelling switch engages with the cams in the lift shaft, thus operating the micro-motor. The micro-gear will then automatically lower or raise the lift until it is absolutely level with the floor, when the levelling switch will interrupt the circuit of the micro-motor and stop the car, due to the lever having disengaged itself from the fixed cams on the wall. This position of the car will now be maintained under all conditions of loading, as the automatic control of the micro-motor is independent of the door or gate contacts, i.e. if the position of the car relative to the floor should be slightly changed, perhaps by increasing or decreasing the load, the lever operating the levelling switch will once more come into contact with the cam, and the micro-gear will be started up and immediately return to its proper level.

Of course it is necessary to provide some means of preventing the micro-gear from operating when passing floors at which it is not desired to stop. This is accomplished by means of a magnet mounted on the levelling switch. When the car is being operated from the main motor, this magnet is energized and prevents the levelling switch from engaging with the cams in the lift shaft. When the power is cut off from the main motor this magnet is de-energized, and if the car is in the micro-zone, i.e. near to but not level with the floor, the levelling switch engages with the cams.

There are no doubt many special applications for such an arrangement, but for the purpose we have in mind at the moment it is questionable if the expense, as compared with that of other methods, is justified. There would also seem to be some danger, if the micro-drive can move the car whilst the gates are open, of a passenger being caught by the toe or in some other way between the slowly moving car and a fixed part of the well—a class of accident which has frequently occurred with hydraulic lifts.

A device to attain the same end—evolved and patented by Mr. Murray D. Scott—is inexpensive and has the advantage that the motor and controller employed are normal in every way and that a certain amount of the energy utilized may be returned to the line. The

Scott automatic decelerator may be described by reference to Fig. 11, (*a*), (*b*) and (*c*). The first shows the normal arrangement of a d.c. motor (compound wound) to the armature of which a winding drum is attached, and having two unequal weights suspended by cables therefrom. If we imagine the armature rotating in a clockwise direction and the machine being started up in the usual way, it will readily be appreciated that on the current being switched off the armature will be brought to rest rapidly, the load L′ being considerably heavier than the load L″. If we now imagine the armature rotating in an anti-clockwise direction, on switching off the current the load L′ will continue to

If the motor be running in an anti-clockwise direction, the preponderance of the weight L′ may cause the motor to generate current. Closing the diverter resistance circuit will put a load on the armature, and additional short-circuiting switches will cause the machine gradually to decelerate as before until the main switch S is finally opened for stopping the machine.

It is found that by correctly calculating the diverting and starting resistances the motor deceleration may be accurately predetermined and will be practically independent of varying loads. An improvement is shown in (*c*), Fig. 11, which illustrates the motor wound with an auxiliary shunt field connected in parallel with

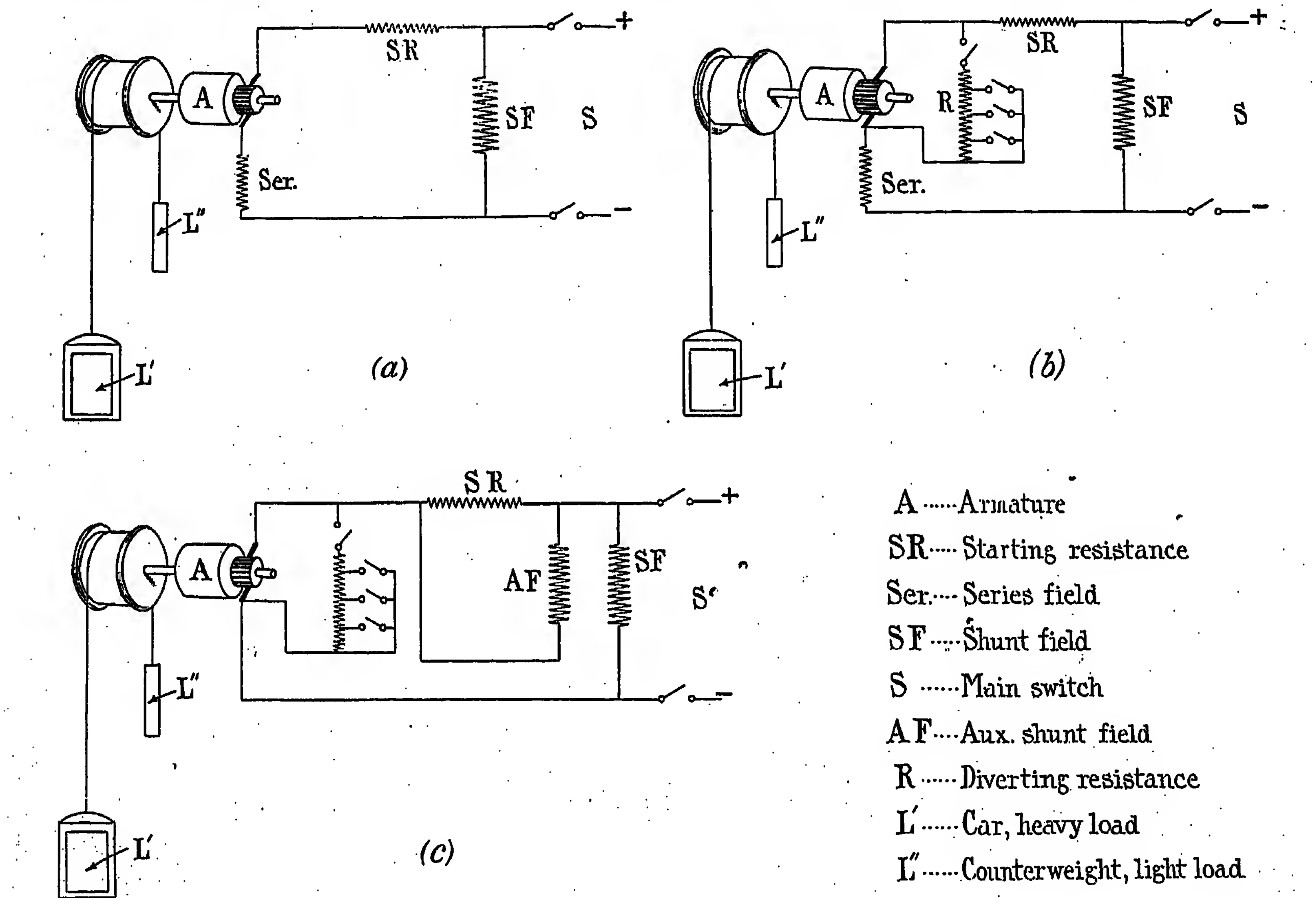


Fig. 11.

exert a rotating torque on the armature shaft, thus prolonging the period of deceleration.

In Fig. 11, (*b*) is a similar arrangement, except that a resistance R is arranged in parallel with the armature, a switch being inserted to throw this resistance in or out of circuit.

Let us now consider the case of the armature revolving in a clockwise direction. If before opening the main switch we close the diverting resistance circuit, the voltage across the armature terminals will be reduced, thus causing the motor to decelerate to any predetermined minimum governed by the additional short-circuiting switches on the resistance R. The motor may be finally brought to rest by opening the main switch S.

the starting resistance. This has all the starting advantages of a heavily compounded machine without the consequent disadvantage of speed variation, the auxiliary field being automatically cut out as the starting resistance is short-circuited, and being again automatically strengthened as the armature voltage is reduced by the decelerator resistance.

A further development of this idea with special relation to automatic lifts permits of comparatively high running speeds being employed with the surety of accurate floor-levelling under all conditions of load. The design, which is termed the "Auto-Pilot," has only recently been protected and is in the experimental stage. Two knobs or large buttons in the car are marked distinctly "up" and "down." On one of these being

depressed the lift accelerates and runs at normal speed. As the car passes each floor a signal light glows, and if the knob or push be released during the period of illumination the car will decelerate and stop level with the next floor.

Although there is no official supervision of electric passenger-lift installations in this country, the percentage of accidents is extremely small and apparently rapidly decreasing, a fact reflecting high credit on the firms responsible for their design.

I have endeavoured to obtain some exact information as to the percentage of accidents, but without success. The insurance companies have been unable to give me any figures, and the Home Office Reports deal with factory and workshop hoists only. I have had a search made of a large number of newspapers over a long period of years and a précis taken of all the lift accidents reported, but a study of these has proved useless, inasmuch as it is usually impossible to discover from the newspaper report what type of lift is referred to, what is the cause of the failure, or exactly how the accident occurred.

One is thrown back, therefore, upon one's own experience, and mine is that the majority of accidents have resulted from one or other of the following conditions:—

(1) Absence of gate and interlock contacts on the car.
(2) Failure of gate locks.
(3) Insufficient enclosure.

It is dangerous to permit a passenger lift to operate without a gate and interlock upon the car. Without interlocking contacts the attendant will insist upon starting the lift, and possibly closing the landing gate after the lift has started, before closing the car gate, and quite likely the car gate will never be closed at all. It must be remembered that a certain running clearance between the moving car and the face of the lift well is necessary, and, however smooth the face of the well may be, with this running clearance reduced to a minimum it is always possible for part of the clothing or the foot or hand of a passenger to become jammed between the face of the lift well and the moving car.

The failure of gate-locking devices, in which I include the electrical interlock that prevents the lift from operating whilst a gate is open, has been responsible for a large percentage of accidents. If the lock is out of order it may be possible to open the landing gate and to step into the lift shaft in the belief that one is stepping into the car; or on an automatic lift it may be possible for the car to be moved, by someone operating from some other floor, whilst a passenger is stepping into or out of the car. The remedy is the improved design and construction of the door-locking device, to which I will refer later, but a most valuable contribution to the safety of passenger lifts is to be found in efficient lighting. Too often the lift is stowed away in a dark corner. There should always be ample natural or artificial light immediately facing the lift entrance, and the car itself should be illuminated.

It is very difficult to persuade architects, builders or property owners of the necessity of carrying the enclosure above 6 ft. 6 in. in height in stair wells and other open places. A lift enclosure should be what its name implies and not, as many architects seem to think, a means of expressing their architectural ambition in iron and bronze. An enclosure which will allow an arm or leg to be thrust between the bars or below the bottom rail is dangerous, and there are hundreds of such enclosures in London. Cleaners and others will reach through on some pretext or other. The triangular space above each stair tread is a particularly dangerous point and should always be filled in. Apart from the danger to cleaners who thrust their arms and brooms through, articles—bottles sometimes—dropped on the stairway roll through here, and I have known a heavy bottle to smash through the top of the car. Dirt and rubbish is swept from the stairs through these convenient openings; this litters the top of the car and attaches itself to the greasy guides.

Upon the counterweight side, at least, the enclosure should extend from the floor to the ceiling, the reason being the large percentage of accidents which have occurred to cleaners, painters and others reaching over the enclosure for one reason or another, and, whilst observing the lift car, failing to notice the descending counterweight.

It is also often desirable to fit a wire screen in the well at the point where the car passes the counterweight, for the protection of men who may be working on the top of the car—always an occupation of considerable danger. For the same reason a screen should be fixed in the pit so as to protect any person engaged in cleaning out the pit, from injury by the balance weight.

Collapsible gates should be constructed on the "mid-bar" principle, so that the space between the bars is insufficient to tempt any person to try to put his hand through for any purpose whatever.

I have briefly referred to what I believe to be the three principal causes of accidents in connection with electric passenger lifts. I shall now endeavour to review the subject more closely by suggesting the various possible types of accident and the preventive measures to be taken in each instance.

The moving car or counterweight may come into collision with some dislodged portion of the lift enclosure or with some article projecting into the lift well.

Counter provision.—The enclosure must be sufficiently substantial to prevent this possibility, and there must be no opening or ledge upon which it is possible to rest any article with which the car or counterweight may come into contact.

The car coming into collision with the permanent stop at the top or bottom of the well, owing to the attendant omitting to operate the control circuit.

Counter provision.—Limit switches fixed in the well and operated by a ramp on the car and so connected as to open the control and brake circuit.

The car coming into collision with the permanent stop at the top or bottom of the well owing to some failure of the electric circuit rendering the control and the control limit-switches ineffective.

Counter provision.—Main limit-switches operated by a ramp on the car and so fixed and connected as to cut off the main electricity supply at both poles upon the car passing a certain distance beyond the top or bottom

floor. It will be noted that the brake, being normally in the " on " position and held off when the car is running only by means of an electric solenoid, must come into action when the main circuit is opened.

The car colliding with the permanent stops at the foot of the well due to excessive speed, the result of failure of the motor field circuit.

Counter provision.—A centrifugal governor gear operated by a cord attached to the car and so designed that a fixed excess of speed in the downward direction causes the main supply circuit to be opened and a safety gear attached to the car sling to come into operation. The function of this gear is to stop and support the car by means of grips pressed and wedged on the guides or guide backings.

The car coming into collision with the girders at the head of the well, due to a similar cause.—This cannot occur if the traction drive is employed and the counterweight allowed to land before the car reaches the permanent stops. Shock due to the counterweight landing at high speed may be minimized by the use of suitable buffers. In the case of drum-winding machines the only safeguard against this class of accident usually employed is the limit-switch and extra clearance for over-run of the car.

The centrifugal governor as usually employed is operative only in the downward direction of travel, but it can be designed to arrest the motion of the car in case of excessive speed in either direction.

The car falling due to failure of support.—This may occur in the case of :—

(*a*) *The car becoming jammed in the well whilst the ropes continue to be paid out by the engine above, and then becoming free and falling to the extent of the slack rope.* (*This is a class of accident confined to drum-driven lifts.*)—In the case of traction drive, if the car or counterweight jam, the result is either an extra load which causes the main fuses to blow, or a relief of load which causes the traction sheave to revolve harmlessly within the slackened rope. In the case of drum drive the counter provision is the slack-rope safety switch applied to both car and counterweight ropes in such a way that if any one of these ropes slackens, the switch will operate and cut off the main supply current.

(*b*) *Fracture of the supporting ropes.*—The counter provision is a safety gear attached to the car sling and operating as above described, to support the car by friction upon the guides in the event of the ropes breaking. In the best form of such safety gears the wedging action takes place and the car is brought to rest in the event of any one of the supporting ropes stretching beyond a certain limit. As a rope invariably stretches before breaking, the result is to anticipate a break taking place. If the well is totally enclosed and fitted with doors necessarily locked before the car can be set in motion, it is possible to use the column of air below the car as a cushion to prevent the too rapid descent of the car. Suitable buffers may also be employed as an additional protection.

(*c*) *The ropes becoming disengaged from the winding engine.*—This is a most serious class of accident, because if the safety gear on the car is operated by the supporting ropes themselves, or by a cord passing over the same sheave and therefore probably disengaged like the ropes, the result is that the safety gear is inoperative and the car and counterweight fall together without any brake. Ropes may leave the top sheave during the momentary slackening due to a jam of the car or counterweight, and from other causes. The counter provision is the employment of a centrifugal governor or other device to operate the safety gear by means of a cord reeved over pulleys entirely independent of those over which the supporting ropes pass. In this connection the extreme danger of using an overhung traction sheave may be noted. There should always be a substantial bearing on each side of the sheave so that the ropes—if by any means they are thrown off the sheave—cannot fall clear.

Three typical forms of safety gear, as usually applied to the cars of passenger lifts, are illustrated in the lantern slides.

The safety gear is now usually fixed below and not above the car. This is a wise precaution, as cases are on record in which the car has become detached from the gear fixed to the sling above and has fallen unchecked into the well.

It is not usual to attach a safety gear to the counterweight, except in places where the well does not descend to the lowest level and the counterweight might therefore fall into an inhabited space. Nevertheless, if it were the invariable practice to equip the counterweight with safety gear a few accidents might be rendered less serious in their effect.

(*d*) *Failure of a portion of the mechanical gear allowing the traction sheave or drum to revolve under the influence of the loaded car or counterweight.*—This may happen if the keys fixing the sheave or worm-wheel fail, or the rim of the worm-wheel becomes detached from its centre, or the teeth of gears wear out or fracture. The only preventive, apart from sound design and construction, is regular inspection, but, if the lift is allowed to get into a state in which such an accident can occur, the centrifugal safety gear—if designed to operate in both directions of travel—will check and support the car.

A passenger becoming crushed between the moving car and some portion of the lift well.—This cannot happen if a gate is fixed to the car entrance and so interlocked by means of a contact on the gate with the control circuit that it is impossible to move the lift unless this gate is completely closed.

Car starting whilst passenger is entering or leaving.—The counter provision is electrical interlocking contacts on both landing and car gates, preferably connected on opposite poles of the circuit.

Falling into the lift well.—The counter provision is a mechanical lock upon each landing gate, rendering it impossible to open the gate from the outside unless the car is at the landing in question. These locks are released by a ramp on the car which operates a roller connected with the gate lock.

A gate lock, to be absolutely reliable for use on an automatic lift, has to meet a great many requirements, and many of those already installed are defective in one way or another. Locks are now available which do meet all requirements and are safe. Existing locks of the older types should be exchanged for these.

One of the conditions of the perfect gate lock is that it shall not allow of the gate being opened when the car is only passing and not stopping. This condition can be complied with by the employment of a movable solenoid-operated ramp on the car, but the complication is not usually considered worth troubling about, because the effect of opening a gate whilst the car is passing is only to stop the lift, and the result, though annoying to the passengers, is not dangerous.

The other accidents which may occur on electric passenger lifts mostly concern men engaged upon construction or maintenance and do not come within the reach of this paper.

It will be observed that in order that a passenger lift may be safe it must be provided with a number of mechanical and electrical safety devices. In the design of these the guiding principle must be that any failure of the safety device itself, whether mechanical or electrical, shall only result in rendering the lift inoperative. If this principle is faithfully carried out the lift will be put out of use upon the least derangement of any one of the large number of minor parts. The only steps which can be taken to prevent this are regular inspection and adjustment by men trained to the business.

As it is not desirable to allow wearing parts, ropes, bearings, gear, etc., to wear to anything approaching breaking point, inspection is necessary to ascertain when renewals should be made. The frequency of such inspection may vary considerably, according to the amount of service the lift is called upon to perform, but I have found it reasonable to insist upon an inspection after every 6 000 journeys, with a maximum interval of three months between inspections.

Discussion before The Institution, 17 January, 1924.

Mr. W. S. G. Baker: The author suggests that it is necessary in this country for a special type of lift to be developed, and implies that the types of lifts used in America are not quite suitable for this country, but I do not understand why this should be so. There are many places in America where the conditions must be exactly similar to those existing here. I do not, of course, mean to suggest that that is a reason for not seeking improvements. I am in agreement, from rather a different point of view, with the author in his remarks regarding the location of lifts by architects. It is quite usual for an office lift to be placed in the basement, generally next to the boiler, where the conditions, both mechanical and electrical, are by no means of the best. The cost of maintenance of such a lift must necessarily be greater than if it were placed at the top of the shaft. The question of lift speeds is almost entirely one of control. The kinetic energy in a lift will vary as the square of the speed, and therefore the stopping of a lift at high speeds is distinctly difficult. In this country the majority of lifts running at ordinary speeds are stopped by the current being switched off and the brakes being applied. That is satisfactory under some circumstances and at low speeds; but with high-speed lifts, or lifts which have to deal with considerably varying loads—for instance, a railway lift with a load of either nothing or 60 or 70 passengers—it is necessary to reduce the speed of the lift to some predetermined constant. The author shows in Fig. 11 how this can be done by means of dynamic braking. The system illustrated in Fig. 11 (*b*) is almost identical, in fact, with that in use on the Underground Railways' lifts. The periodic variations of the acceleration curve shown in Fig. 6 (*b*) are very curious, and it occurred to me that they might be, in part, due to variations in the torque of the motor, and also to variations in the angular velocity, due to the fact that the gear is a worm gear, which gears are sometimes not very easy to control so as to give an absolutely uniform speed. I agree with the author that ropes of not too high a tensile strength will undoubtedly last longer. In many cases I have found it an advantage to use ropes of a heavy-gauge wire rather than of very fine-gauge wire, particularly where a sheave is driven by the rope and moves along a shaft, with a tendency for the wires to be plucked out. Nearly all our lifts are built with S bends, and these cause much wear on ropes, more particularly on the counterweight ropes. The author does not refer to the methods adopted for attaching ropes to the car and to the counterweight. It is absolutely essential that the strain should, as far as possible, be equalized throughout the wires of the rope. We have tried a number of different methods. The first was the spliced eye, and we have finally adopted a metalled-in end somewhat on the same lines as a colliery fixing, choosing a metal of rather definite proportions which seemed to give very good results. Our fixings will actually withstand a greater strain than the rope. On the question of the position of the worm, my own personal preference is for the worm to be below the wheel, for this reason: there is no perceptible difference in the two cases as to lubrication while the load is on, but when the lift has been standing for some time, if the worm is above there is a tendency for the oil to be squeezed out from between the wheel and the worm, owing to the constant weight on the machine. The result is that the worm has to start and the wheel has to make some part of a revolution before any oil is carried up to the working faces. If the worm is below, it is constantly immersed in oil and a partial turn of the worm is enough. The design shown in Fig. 8 appears to be very ugly, as determined by the height of the centre-line of the motor shaft from the bed plate, due to the motor height. I see no reason why a special motor should not be developed in this country for lift work. The first consideration is that the armature should have low mass and small radius. The author refers to gearless lifts developed in America. I have had the opportunity of seeing these lifts, and from a maintenance point of view I think rather highly of them. They have only two bearings, and there is nothing else renewable in the ordinary mechanical wearing sense. The machine is more costly, but with a 2 to 1 roping on the car and on the counterweight I think it is a very attractive proposition indeed, more particularly if one is not tied down to a low speed.

There is another interesting point of difference between American practice and English practice. The English lift manufacturer seems to rely for control very largely on sliding contacts, the bulk of the lift controllers being more or less motor starters. The American gear is almost entirely built up of what are known as "clapper" switches, and from a maintenance point of view, as there is very great difficulty in these days in getting really skilled men, this type of switch is, in my opinion, far preferable. It should be quite easy to renew the contacts, and I have found the gear to give very little trouble indeed. I am entirely in agreement with the author's views on the question of safety devices. I have urged these views from time to time. On the Underground Railways we interlock very much in the manner indicated by the author, although we may not be quite so up to date in some respects.

Mr. J. T. Mould: I am particularly interested in the author's statement in regard to the importance of acceleration and deceleration. All the examples which he gives refer to direct-current lifts, but I should like to hear his experience with alternating-current lifts, particularly with regard to deceleration. The device patented by Mr. Murray D. Scott, which he mentions, is one that I saw used about the year 1902. At any rate the principle of the armature diverting-resistance was used and the same principle was adopted by the Cutler Hammer Manufacturing Co. in connection with cranes as long ago as 1898 or 1899. It is quite possible to get perfectly reliable and smooth deceleration and acceleration, but the control apparatus must be very carefully designed. Mr. Baker mentioned the superiority of clapper switches over sliding-contact switches. My company used to supply a great many lift controllers with sliding contacts, but now all our designs have butt contacts.

Mr. B. A. Siden: The maximum capacity of a building is a very vital factor in arriving at the lift equipment. The author of the present paper is rather in disagreement with the American figures and those given in Mr. Day's paper, but they tally with my experience, i.e. they run from 80 to 100 sq. ft. per person in office buildings. From the rest of the information given in the paper, it will be more easy than formerly to deduce the lift service required. One important point which the author raises is that the specialist is too seldom consulted in these days with regard to lifts, which are becoming more complex every year. The most important thing in connection with a lift is the maintenance, and this has a very considerable bearing on the question of design. There is a great difference of opinion between the relative merits of sliding contacts and clapper, or contactor, types of contacts. A great difficulty is, in my experience, to get the maintenance staff properly to maintain a sliding contact. If that were done I should always prefer a sliding contact where it is allowed to be self-cleaning, i.e. where the pressure is correct and where the surfaces are ample in area and the current density consequently low. If a carbon-block contactor gear is adopted it is essential to keep the current density very low. In many of these devices the current density is high, with the result that the contacts, flexible connections and springs become heated in the course of the day's run. I am of opinion that the running of lifts should be governed by regulations, but until that is done people will be inclined to scamp the maintenance because it is expensive, with the consequence that the lift may be allowed to run until a breakdown occurs. I have had experience of lifts by almost every maker and under varying conditions and I prefer the over-driving worm. The worm is the portion of the worm-gear which gets the most wear, as the wear occurs practically on one tooth of the worm, whereas on the wheel it is distributed completely round the periphery of the wheel. When the worm is above it is very easy to inspect, but if it is underneath it involves opening an inspection door and removing the oil from the gear case. The fitters will not do this unless they are specifically instructed. There are several makes of winding gears which have unbushed bearings. The result is that in a few years the whole of the gearcase may have to come out and be put on to the boring machine, which is a big and costly operation, whereas if the bearings had been bushed the only renewal necessary would have been two gunmetal bushes at a cost of, say, £5. With regard to the question of the height of centres, in a high-speed lift there is bound to be some vibration, however well the armature of the motor is balanced. The higher the centres of the main shaft, the more the vibration is transmitted through the ropes to the car. By keeping the main driving-shaft centres low, I find that the vibration is kept within reasonable limits. I think that the question of alternating-current lift practice should have been raised. Alternating current is becoming more and more important through the activities of the Electricity Commissioners, and its use is being developed considerably, especially in provincial areas, and the application to lifts will cause difficulties, as at the present moment the practice in regard to alternating-current lifts is, I consider, very much behind. There is a type of controller known as the "eddy-current control" in connection with two- or three-phase lifts, and for simplicity it cannot be excelled. It consists of the usual rotor with three slip-rings, and a double-pole reversing contactor for the stator. The three-core choker is connected across the slip-rings and takes charge of the heavy currents which occur when the stator circuit is closed. This apparatus can also be used as a dynamic brake, but, of course, is only suitable for polyphase work. Much development is needed in motors and control gear for single-phase a.c. lifts. I think that few people will dispute the fact that the top of the shaft is the ideal place for the winding machine. The question of roping is very important, and it is not only the cost of the ropes which is of consequence but the cost of fixing also, and this is usually about 40 per cent of the cost of a set of ropes, so that the saving in the cost of rope renewals by proper selection of machine position is very considerable. In general, my experience is that unless high-speed lifts are limited to certain floors in a building no advantage is gained. In a building of 9 or 10 floors a real advantage is only gained by using express lifts to serve floors above the third or fourth, but the better way is to employ a fast and a slow lift, and let the latter take charge of the intermediate traffic

and the lower floors, leaving the upper floors to the high-speed lift. Failing that, if there is only one lift and that has to serve the whole of the building, a moderate speed of about 250 ft. per min. is best.

Mr. B. P. Walker : The author mentions the inadequacy of the services provided in most of the buildings in the city. As time goes on and building restrictions are less limited, the height of buildings will be still greater and there will be still more demand for lifts. A large amount of consideration has been given to the question of acceleration during the past few years, and present-day and future lifts will accelerate faster than the old ones. The important point is to aim at even acceleration, no matter how fast this is. The author refers to the micro-drive lift, which possesses the advantage that it stops dead level with the floor under all conditions of load and speed. In addition, it is self-levelling should the position of the car vary due to the variation in the load. For example, should a very heavy load be pushed in on a trolley, when the front wheels enter the car the lift will drop, due to the stretch of the ropes, but the micro-drive lift automatically levels itself so that the back wheels of the trolley can be wheeled straight on. The automatic decelerator was mentioned by one speaker as being an old method of connection. To my knowledge the same forms of connection have been used for many years not only in lifts controlled by a car switch but also in those operated by a push-button. As Mr. Baker remarked, most of the lifts on the Underground Railways are arranged in this manner. That method of connection does not, however, give absolute accuracy in the stopping of a lift, and it cannot effect automatic self-levelling, so that, while it is claimed to attain the same ends as the micro-drive, it is a rather different proposition and will not meet the same conditions. Moreover, when applied to alternating current, which is becoming more and more common in this country, the micro-drive is quite a simple matter, whereas I think there would be some difficulty with regard to the automatic decelerator.

Mr. W. D. Brakenridge : I agree with Mr. Walker that the micro-drive is a very sound proposition. In regard to the automatic closing of the gates, there are on the market a good many fittings which appear to achieve this object satisfactorily. It is stated in the paper that the percentage of accidents is small. This may be so, but it should be less. Gate locks will reduce the risk to a large extent, especially in the case of hydraulic lifts, very few of which are to-day fitted with electrical interlocks, or locks of any description. In Denmark locks are compulsory. Dual control, i.e. alternative car switch or push-button control, is a great advantage in a number of cases, especially in hotel lifts.

Mr. P. Good: In the early part of the paper the author refers to the need for fundamental terms and definitions, so that people interested in the subject can understand each other more readily. It may be of interest to mention that the British Engineering Standards Association is preparing a comprehensive list of electrical terms and definitions which, with the author's help, could be made to meet his requirements. The author has set himself the difficult problem of gauging the lift requirements of buildings. I think that he attaches rather too much importance to the total number of people using the lift at one floor, as the majority walk down. For lifts in London, where there are a large number of comparatively small buildings, the delay is very largely caused by the human factor, and the automatic lift which returns automatically to the ground floor should be much more widely used. In office buildings of three, four or five stories, an automatic lift returning to the ground floor, with satisfactory automatic door-closing, would most frequently meet the requirements and eliminate much of the human factor. The author refers to the safety gear for preventing a lift from falling in the event of the ropes breaking. On one occasion I was asked by a lift maker to satisfy the consulting engineer that his gear would, in the event of the ropes breaking, actually stop the lift within 12 inches, in accordance with his guarantee. We took a bight in the ropes with a slip hook, leaving a fairly considerable amount of rope loose, and loaded the lift to its full capacity. We then started the lift downwards until it was travelling at full speed, and released the slip hook at a predetermined place. The lift pulled up within 8 or 9 inches. It was the only time that I have ever seen the safety device on a lift actually tested, and it was quite a damaging and expensive test. Perhaps by now a simpler test is available, as it seems desirable to have a suitable means of testing safety devices.

Mr. W. R. Rawlings : Can the author say why the continuous lift was superseded ? The paper makes no reference to the cost of energy in connection with electric lifts, and it would be interesting to know how it compares with that for hydraulic lifts. In one case where I put in a service for a push-button-call lift, the proprietors were agreeably surprised to find that the total bill per week was only 1s. 6d., although it was open for the use of the public and their own staff. One interesting installation with which I had to deal was an isolated case of a 2-ton goods lift to serve six floors in a large furnishing warehouse. The plant consisted of a 4-h.p. gas engine with a 190 ampere-hour battery working at 200 volts. A test was applied by running a 2-h.p. motor and twenty 30-watt lamps for one hour. During this period the lift was operated 30 times from basement to top floor with a 2-ton load. At the end of the test the battery had only discharged one-third of its total capacity. The first year's gas bill amounted to only £10, again illustrating the very low cost of running an electric lift.

Mr. H. Marryat (*in reply*) : I agree with Mr. Baker that there are many places in America where the buildings are similar to those in this country, but I do not agree that the conditions of traffic are the same or that calculations arrived at from counting lift traffic per occupant of a building in America are applicable to a similar class of building in Great Britain. Big variations in lift requirements are found to exist in different American cities, and there are still greater differences between American and European requirements owing to variations in the conditions of employment, daily routine, and psychological reasons.

The suggestion that the periodic variations in the acceleration curve shown in Fig. 6 are due to the fact that the reduction gear employed is the worm and wheel type is distinctly interesting. It was suggested in the paper that this effect is due to a combination of

causes, and possibly this is one of them. The whole matter is being investigated further with improved apparatus.

Passenger-lift engineers do not generally experience trouble due to the ropes failing at the point of fixing to the car or counterweight, such as is common in mining and large public railway lifts, the reason being that the smaller sheaves and sharp bends which have to be negotiated with the ordinary passenger lift cause the rope to wear or fracture at the running surface before fracture develops at the fixing.

I note with much interest Mr. Baker's preference for the arrangement of worm gear with the worm below the gear wheel, in order to secure lubrication of those teeth of the wheel which come first into engagement when the lift is started after being at rest for a long time. I do not think that this applies to the class of gear which we are using for the ordinary passenger-lift service in which a considerable amount of oil collects in the hollows of the worm-wheel teeth standing at the top, so that when after a considerable rest the gear is set in motion there is still sufficient oil to lubricate immediately the worm and the few teeth which immediately follow, until the part of the wheel which has been resting in oil comes into engagement.

The suggestion that a special motor should be developed in this country for passenger-lift use is excellent. Attempts have been made in this direction, but owing to different makers each developing his own particular motor, spare parts are apt to become expensive. This is a difficulty which might be overcome if it were possible for lift makers to co-operate with the B.E.S.A. in the standardization of leading dimensions.

With regard to the use of clapper switches, the advantages are mostly on the side of reduced cost of manufacture. Owing to the ease with which gear of this type may be standardized, the parts can be turned out at a very low cost. My own company, in common with other lift makers, has employed them to a large extent in the construction of lift controllers. There is, however, an outstanding objection to clapper switches in the noise which they create in operation. The sliding-contact type of controller is practically silent and when properly constructed requires no more attention.

In reply to Mr. Mould, the difficulties which are supposed to exist with regard to alternating-current lifts can be solved in a great number of ways, and it is a question rather of experience and choice between them than anything else. Two-speed squirrel-cage motors are satisfactory where the stops are not too frequent, but as the starting energy and the braking energy from high speed to low speed are entirely dissipated in the motor itself the machine is likely to overheat if the stops are frequent. In such cases another solution must be sought.

With regard to the devices patented by Mr. Murray D. Scott and referred to by both Mr. Mould and Mr. Walker, I understand that there is no claim of novelty as to the diagram employed but only as regards the practical means adopted to put this diagram into effect for starting and decelerating an electric lift—especially one running at high speed.

With regard to the remarks of Mr. Siden, I do not wish to question the American figures of 80 to 100 sq. ft. per inhabitant for certain classes of building, but I do say that the use which the inhabitants of a building and their visitors make of the lifts in London is not that of the same number of people in New York. I am in entire agreement with Mr. Siden in his remarks regarding sliding-contact switchgear, and I am glad to note that with his long experience he is able to support the views expressed in the paper as to the best arrangement of the worm and wheel and the best position for the gear in the lift shaft. I need hardly say that I am in agreement in condemnation of unbushed bearings in the gear box.

As Mr. Brakenridge observes, there are many devices for effecting the automatic closing of gates, but I know of none which is at once effective and reasonable in cost.

I am glad to hear from Mr. Good that the British Engineering Standards Association is prepared to include lift terms in its comprehensive list of definitions now in preparation, and I shall be very pleased to assist in any way possible. Mr. Good has referred to the automatic lift which returns automatically to the ground floor. This is an excellent solution of certain specific propositions, but has its limitations. Such a lift is a positive annoyance where the down traffic is considerable, as a person wishing to go down must wait for the lift to come up unless he happens to catch it at the particular floor where he is waiting. The method of testing mechanical safety-gear is that still usually employed. Governor safety-gear may be tested by increasing, by means of a field resistance, the speed of the motor above the prescribed maximum.

Mr. Rawlings has pointed out my omission of any reference to the energy consumption of electric lifts and has given some interesting examples. In the paragraph dealing with the total cost of lift service, I referred to energy consumption as an item. It is a small one compared with the more important items—rent, maintenance, interest upon capital, etc.—a point which I have endeavoured to emphasize. The energy consumption of similar lifts running under different conditions will vary very much because acting upon the see-saw principle, with the average load counterweighted, the running current is only considerable with full load or no load and is negligible with average load. It has often been found possible to effect a large saving in energy consumption by adjusting the counterweight after the average load has been ascertained. This should always be done where a lift has been installed of too large a capacity for the work which it is subsequently called upon to perform. This principle is of even greater importance when dealing with goods-lift installations where the conditions of average load sometimes alter completely with a change of works' routine.

In reply to the question as to why the continuous running lift has been superseded, the reason is that in order to allow passengers to step on to and off the continuously running cars the speed must be so low as to be inconsistent with modern requirements. The successor to the continuously running lift is the escalator in which the very slow motion is compensated by the fact that there is no waiting for a car, and by the possibility of shortening the travelling time by walking up or down the steps of the escalator.

North-Western Centre, at Manchester, 8 January, 1924.

Mr. H. C. Crews: In his opening statement the author says: "Where electricity is available, it has practically superseded all other forms of energy for new construction." I agree with that statement if the author will add the qualification "if the price of energy allows electric driving to be a commercial proposition." I do not think he meant to convey that in his opinion electricity is always preferred for driving lifts irrespective of the cost of energy. In a place like the West End of London, say in Bond-street, we do not look for a commercial proposition as we should in Manchester, where we do expect to buy things cheaply. I am responsible for a lift which is running in Bond-street, London, where the supply undertaking charge $1\frac{1}{2}$d. per unit. For similar machines used in Ancoats, Shudehill, or almost anywhere in Manchester to-day, the lift rate is $3\frac{3}{4}$d. per unit. There is also a municipal high-pressure hydraulic supply in Manchester, but I do not think that that quite accounts for the difference. The same firm who use an electric lift in Bond-street also have a similar office block in Manchester, and there they have had a hydraulic lift installed. I could not persuade them to use an electric lift. Both are modern up-to-date machines doing much the same work and the cost of energy was the deciding factor. I quite agree with the author's remarks in regard to specifications for lifts. A number of the leading architects do realize that this is rather too technical a matter for them, but there are thousands of architects who expect good results without technical knowledge of the subject, and too late in the day ask makers to quote on the very brief specification which they have drawn up. I cannot agree with the author's remark on page 332 that "Serious danger attaches to the drum method of driving," etc. The V sheave or the drum-drive alternative is a very old controversy, and there is much to be said on both sides. I agree that more sheave drives are put in, mainly because they are cheaper, usually simpler, and to some extent more efficient; but there are many advantages in the drum drive, particularly in cases of heavy weights, for which purpose I consider them to be usually the best practice. The author says that rope cost is a very serious factor in the cost of a lift, but I have only once in a long experience had to renew drum-driven ropes. If of suitable quality, a useful life of from 10 to 20 years can be certainly expected on an average drum lift, but the sheave-driven rope has, in my experience, an average life of about 5 years only—on a fairly busy lift in each case. I also disagree with the author when he says: "The cost of maintenance of an electric passenger lift in business premises varies from about £20 to £100 per annum." I think that those figure are too high. In 1906 I obtained from users, or my own records, the actual maintenance figures of 12 hydraulic lifts, and the average cost was only £10 2s. per annum. I also took 12 electric lifts and their average maintenance cost per annum was actually £9. Allowing for the difference in present-day values, I think £20 should be a maximum. It must be a very busy or expensive lift where this cost is exceeded. The method of reeving the ropes is, of course, very important. As regards the efficiency of worm drives, I still specify self-sustaining conditions, but always somewhat reluctantly; it seems a pity to confine oneself to something like 50 per cent efficiency when 90 per cent can be easily obtained with a worm. In some of the high-speed long-travel lifts, makers put in a high-efficiency worm and take extra precautions in safety gear. So many good safety gears have been shown in the lantern slides that I feel sure we need not in the future confine ourselves to self-sustaining conditions and introduce the low-efficiency worm. This is what I suggested in a paper which I read in 1906*: "In the author's opinion, if higher efficiency gear is generally adopted by makers in this country for busy electric lifts, a second brake will become imperative. Possibly a modified power band brake, acting on an extension flange of large diameter overhead sheave, and arranged for mechanical operation from cage in case of emergency, may ultimately be adopted, with an 85 per cent efficiency worm gear, in addition to usual electric brake." I do not think that that suggestion has been adopted, and perhaps it is not to-day the best method, but some modification of it would, I believe, prove to be a simple and cheap arrangement. I agree that the combination of press-button and car-switch control is often a most desirable thing. I have in some cases adopted this and found owners very satisfied with it. There is nearly always a slack time on a lift, particularly in such places as hotels. In such cases an attendant is employed to work the car switch, with rather quicker running, for the busy period, and when traffic is quiet the slower automatic press-button control is used. Nowadays most people are able to use a press-button lift intelligently. The double equipment does not cost very much more, if it is done at the outset, and in many cases it results in a saving in wages and proves a great advantage. On page 337 the author refers to a method by which current may be returned to the line. A great deal can be done in that way, but unfortunately the supply undertakings install a non-reversible meter, with the result that the user obtains no regenerative advantage at all. Lift owners may not be authorized to operate substations, but I do not see why they should not have the benefit of regeneration if done in a reasonable manner, and it is an easy matter to arrange. The failure of cage-locking devices is mentioned on page 339, and in my experience that is the principal cause of accidents. The design of a cage lock is much more difficult than appears at first sight, particularly the mechanical part of the design. Even to-day there are only two cage locks that I consider to be absolutely safe. I agree with the author that the cage should be lighted. In one case after an accident had occurred on a press-button lift, due to the lack of light, a key switch was placed in the cage and the light was switched on during all dark periods. In many cases the supply undertaking will charge such cage-lighting at the power rate, and the cost is negligible. I should be glad if, before the

* "Lifts and Hoists," *Journal I.E.E.*, 1906, vol. 37, p. 245.

paper is published in the *Journal*, the author would add some figures of high-speed lifts upon the lines of those I gave in my own paper, showing first cost, maintenance cost, energy cost, etc., as they would be very valuable to the profession and to the engineering trades generally. I have myself taken out some up-to-date costs of half a dozen typical and most usual types running at from 150 to 200 ft. per min. with 7- to 15-cwt. loads and 40 to 60 ft. travel. I do not think that the cost of energy of more than one of these exceeds £10 per annum. The one exception is a very busy, rather high office block in Manchester, and in two years it has averaged only 1 099 units per annum. A Manchester cotton warehouse employing a lift for their goods uses only 355 units per annum over a three-years' average. A fairly busy 15-cwt. lift in a block of chambers consumes 666 units per annum over a six-years' average. A rather busy clothes warehouse over a three-years' average uses 563 units per annum. A busy hospital, with a bed lift which is used a good deal for patients, only averages 404 units per annum over six years. A rather busy office block in London has averaged 614 units per annum over two years. If power can be obtained at, say, not more than 2d. per unit, the cost is very low; even at 3¾d. it does not amount to anything serious and compares very favourably with most hydraulic charges for similar duty.

Mr. C. E. Raeburn: In view of the further and closer investigations now being made, I would suggest that the author in his reply to the discussion give, if possible, an explanation of the large variations in the rate of acceleration during the accelerating period as shown in, say, Fig. 6 (*b*). These variations are of great interest, but at the same time it would appear to me that the method previously adopted of investigating the acceleration period may have tended to exaggerate the changes unduly. There seems to have been some timidity on the part of lift engineers in this country in hitherto limiting the speed to 400 ft. per min. I would suggest that those engineers study the subject of the design of electric winders which also carry passengers, run at speeds up to 4 000 ft. per min. and are really super-lifts. Acceleration in such lifts may be as much as 6 ft./sec./sec., and hand-decking is accurate. The study also of what has been done in semi-automatic blast-furnace hoists and chargers would also broaden the view. A table hoist, for instance, works at speeds up to 600 ft. per min., acceleration up to 2 ft./sec./sec., and unbalanced loads up to 4½ tons with cages weighing from 2 to 4 tons. They are started by hand control, and retarded and decked level automatically. Ward-Leonard control is generally used. One speaker in the discussion has described passenger lifts as being highly efficient, but presuming he referred to the more general type of d.c. drive, the contrary is the case, as in addition to the series resistance losses in the controller there are large losses due to the diversion of the armature current during starting and stopping. The tendency now in the United States seems to be to install Ward-Leonard control with and without "weak field" speeds, for the purpose of obtaining advantages of efficiency and safety, better acceleration and speed control with little loss. It appears to me that it is on these lines that the future high-speed, high-efficiency lift should be developed in this country.

Mr. A. B. Mallinson: The author refers to the excessive rope wear which takes place with the arrangement shown in Fig. 7 (*f*). I have had the same experience with cotton rope driving, and the conclusion that I came to was that the trouble was due to bending the rope in the reverse direction almost immediately. Even a slight bend will affect the fibres of the rope very materially and shorten their life. I suggest that the same reason may account for the short life of the steel ropes with this system of reeving. On page 330 the author refers to accelerations up to 300 ft. per min. in a distance of 24 inches. That will result in a rather large peak load relative to the motor horse-power, which will possibly cause the supply undertaking to charge a somewhat higher power rate.

Mr. G. F. Sills: A previous speaker referred to the effect on the human frame of rapidly accelerating lifts. I found this most noticeable on the very high buildings in the United States and Canada, particularly after about 10 to 14 stories. Presumably, matters cannot be mended, as for commercial reasons the lifts must be made to travel fast on these extra high buildings; otherwise extra lifts would be needed to carry the traffic. I could never understand why in buildings costing, say, £100 000, there should often be such inadequate lifts. One sees notices to the effect that only so many persons may be carried, a number which does not at all fill the lift, and the attendant has to refuse waiting people when there is plenty of room. Surely a lift serving large blocks of offices should be capable of dealing with as many people as can be got into it, and there should be no question of the rope, the mechanical parts of the lifts, or the motor, not being large enough to deal with an extra passenger. I am inclined to think that when the motor operating the lift is unduly cut down, and on occasions when one person more than the authorized number is taken in, the slower acceleration of the lift is quite noticeable. Offices in a high building, even on the fourth and fifth floor, are of no use to anyone unless there is a very reliable lift.

Mr. J. S. Peck: I think that the irregularities in the acceleration curve may possibly be due to the elasticity of the ropes. I have seen deep wells being drilled by means of a very heavy tool on the end of a long rope. The action in this case was as though there was a weight on the end of a rubber string, where the vertical movement of the top of the string may differ both in time and amplitude from the vertical movement of the weight. In order to get the movement of the tool to synchronize with the crank for lifting the rope, it was necessary to adjust the engine speed very carefully. It seems possible that a somewhat similar action takes place on a lift, where, due to some inequality in the controller, the rope is suddenly stressed and, being elastic, stretches: the lift tends to follow the rope, but at a later period, and thus oscillations are set up which may appear as irregularities on the acceleration curve.

Mr. T. E. Herbert: It has been said that there is nothing that the mind of man can conceive which is so absurd that some fool will not do it, and that would appear to be literally true of many lift accidents. For

example, a certain lift had a double gate, locking in the centre. The attendant had not shut this outer gate properly, and actually put his hand through the inner gate to close the outer one, and with the other hand put on the current, with the result that his hand was seriously injured. Lifts should certainly be made quite foolproof, and it is essential that round the lift locks there should be a plate which would render it impossible for anybody under any circumstances to get at the outer lock from the inside. If an attendant has failed to close the well gate, it must be physically impossible for him to get at it until he has opened the car gate. I think also that in every case there should be a gate not only on the well but also on the car, and both of them should be locked. For alternating-current lifts it is very convenient to have a direct-current supply to operate the controls. In very many cases considerations of safety would render it worth while to install a battery of accumulators and a small motor-generator for the purpose. Post Office practice generally aims at a maximum of safety. I am glad that the author draws attention to the precautions necessary when the attendants are dealing with the maintenance of lifts. In some cases serious risks are taken as the result of familiarity.

Mr. H. C. Lamb: Mr. Crews in the course of his remarks criticized the Manchester supply undertaking, but he went on to instance a number of cases in Manchester of large buildings where the power consumption of the lifts was shown to be very small. The explanation of the high price of current in the case mentioned by Mr. Crews is that tariffs have to be arranged with due regard to the relation between the consumption of power and the demand. If the load factor is very low, the price per unit must be high, but with a reasonable load factor the price per unit for lift motors would be only a small fraction of that quoted by Mr. Crews. Mr. Crews's ideal supply for lift work would evidently be a low price per unit and a reversible meter, so that at the end of the quarter the amount of the bill would be negligible. I believe that there are at present over 1 000 lifts on the Manchester mains, and no doubt the effect of the reduction in charges (which comes into operation this month) will be to increase this number.

Mr. H. Marryat (*in reply*): In his opening remarks, Mr. Crews seems to suggest that with electricity at 3¾d. per unit hydraulic power is preferable for lift service. For ordinary passenger lifts I cannot agree, and I think that Mr. Crews answers the point himself when he says, at the end of his remarks, "if power can be obtained . . . even at 3¾d. it does not amount to anything serious and compares very favourably with most hydraulic charges for similar duty." Mr. Lamb deals with this point later in the discussion. I think that Mr. Crews is mistaken in attributing in any way to cheapness the rapidly increasing preference for the sheave drive. A drum-driven lift, as now very often installed, is less expensive because a drum may be employed of smaller diameter than a driving sheave. The worm gear and motor may therefore be of higher speed and less weight. Such a drum drive as I am referring to necessitates the use of leading wheels and is hard upon the ropes. In my opinion the sheave drive has won in the controversy to which Mr. Crews refers, because of its simplicity and safety. I quite agree that where the drum in a drum drive is of sufficient diameter and leading wheels can be avoided, the best rope condition has been attained. I am extremely interested in the figures which Mr. Crews has recorded for the cost of maintenance, but for the class of lift which I have in mind, namely, high-speed and very busy passenger lifts often built to conform with adverse conditions, much higher costs are involved. Some of these lifts make as many as 2 000 trips per day. It will be noted that the figures given date back as far as 1906 and, allowing for post-war increase in prices, he reaches my lower figure, which represents probably a similar class of lift to those he has in mind. The second brake, which should be installed if the self-sustaining feature of the worm gear is abandoned, must certainly act upon the worm-wheel shaft and may be operated electrically in a similar manner to the smaller brake on the motor coupling. The type of brake suggested by Mr. Crews would be in every way suitable and probably less costly than one of the shoe type, for large capacity. I am not in the independent position necessary to give the authoritative figures asked for regarding the prime cost and costs of maintenance and energy consumption of lifts of various types. I suggest that Mr. Crews himself should follow up his excellent contribution to the subject with another, bringing these figures up to date.

In reply to Mr. Raeburn, the further investigation now in hand is not sufficiently advanced to allow of my saying anything further upon the subject of acceleration, but I hope to do so as soon as the experiments are completed. I certainly was not aware that winders were in operation at 4 000 ft. per min., although I have examined and can testify to the excellence of the acceleration attained with machines running up to 2 000 ft. per minute. In view of the probability that 600 ft. per minute will for long remain the maximum economic speed for passenger lifts in this country, it is doubtful if the Ward-Leonard system of control will be adopted to any considerable extent, as the stand-by losses would be likely to outweigh any control economy effected.

Mr. Mallinson fears that acceleration to full speed in a short time and distance will mean an increase in the maximum demand. This need not be so if the acceleration is achieved, as it should be, upon a perfectly smooth curve; indeed, the result would be a distinct improvement upon the usual conditions. In any case, the energy consumption of an electric lift is principally confined to the starting period.

Mr. Sills has called attention to the absurdity of installing lifting machinery of insufficient capacity to raise the car when it is only comfortably full of passengers. This condition is pressed upon lift makers daily by purchasers who insist upon the car being of a size to fill a certain definite space and upon the machine being only large enough to lift a specified load which it is believed will be the maximum and which is less than the capacity of the car. A good allowance for the floor space of the car in a city lift is 2½ sq. ft. per person, and a rather greater allowance, say 3 sq. ft.

per person, for lifts in West End establishments. The machine should always be of sufficient capacity to lift the car so loaded, with a margin to spare.

There is no doubt that Mr. Peck is right in attributing partly to elasticity of the ropes the periodic form of the acceleration curves shown, but I believe that other factors are also involved. I may say that the rope makers are extremely interested and have asked to be kept posted with the results of further experiments, towards which they have made some valuable suggestions.

A number of accidents have occurred in the way described by Mr. Herbert. The true solution of this difficulty is the mid-bar gate, which is so constructed as to make it impossible for the attendant or any other person to put his hand through the bars of the gate for any purpose. On existing gates of ordinary construction a protection may be provided by covering the space around the locking gear, or where one is likely to be tempted to put a hand through, with leather. This will collapse with the gate when it is opened.

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 20 FEBRUARY, 1924.

Mr. W. F. Higgs: In many instances the author refers to American practice; it is a pity that our engineers are becoming copyists rather than maintaining their tradition of originality. The author refers to escalator and other types of lifts, but he has omitted to comment upon the continuous cage type. Although it travels slowly, it carries a large number of people. I have seen a number of these working satisfactorily on the Continent. The author does not say what was the result of switching the 21-h.p. motor straight on to the line. If this can be done, why not adapt series-parallel control to series motors without starting resistance? I should like to ask the author why preference has so often been given in the past to marine thrust bearings rather than to ball thrust bearings; and what are the possibilities of using magnetic clutches in conjunction with a flywheel on the motor. Complications would no doubt arise, as two clutches and reduction gears would be necessary to obtain the reverse; on the other hand, the consumption of power would be less, the motor smaller, and the control more simple. The author rightly emphasizes the importance of "Safety First," and if there is one class of machinery that requires this consideration, it is lifting and hoisting tackle of all descriptions.

Mr. F. H. Mann: Difficulty has occasionally been experienced in obtaining a suitable friction material for the brakes. The chief troubles in this connection have apparently been due to variations in the coefficient of friction, leading to uncertainty in locating the cage. Chattering has also occurred, with consequent discomfort to the passengers. The former trouble is most pronounced in the case of push-button control, frequent adjustment of brake-spring tension being required to cause the lift to stop at the required point. Chattering is probably due to the same cause that accounts for the violent surges recorded by the author as occurring during acceleration, viz. the elastic nature of the suspensory system. In the case of lifts running on alternating current, single-phase solenoids have sometimes been used, usually with poor results. Three-phase solenoids are satisfactory, but it would be interesting to hear whether any device has been introduced to enable the simplicity of the single-phase solenoid to be retained, without losing reliability of operation.

Mr. F. O. Harber: Referring to the remarks that have been made in regard to copying American practice, it should be borne in mind that engineers must obviously be influenced by general conditions prevailing outside their control. This applies particularly to lift engineers. Whereas American lift engineers have had very great advantages over British engineers owing to the rapid progress that has been made in the design of buildings, this rapid progress has caused the lift industry to assume large proportions and consequently more time is expended on design. It is true that conditions vary in the different countries, but surely if we can learn anything from another country it would be a short-sighted policy not to do so. The lift engineer is, unfortunately, not usually called in for consultation until the last moment, and the architect, more often than not, relegates the lifts to some obscure corner which he cannot otherwise utilize, with the result that the ideal aimed at is often impossible. This is evident from the last lantern slide shown by the author. From the author's statement that the maximum lift speeds in this country are 400 ft. per min., and from the correspondence in the *Electrical Review* on this point, the inference might be drawn that higher lift speeds cannot be attained. This is, of course, erroneous, as any speed within reason can be provided for by British lift engineers, the point being that high-speed lifts are not required in this country, as the average service is for 4 floors, and about 10 floors is exceptional. Even in the latter case, however, it would not be necessary to exceed 400 ft. per min. In regard to acceleration, if the rate of acceleration is constant no discomfort should be felt by the passengers. The number of steps of starting resistance may not be directly responsible for the periodic leaps in the curve, but the time interval between each step will have an effect in this respect. I should be glad if the author would say if he has tried cutting out the series field in steps at starting and, if so, what results were obtained. The author gives a regenerative circuit for accurate floor stopping, but this is only applicable to d.c. supplies. Can this difficulty be overcome in the case of a.c. supplies? In push-button operation, what method is used for eliminating interference from the landings during the period between the closing of the car gate and the time of pressing the car push? If a landing push is being pressed, immediately the car gate is closed the car will obviously go to the floor corresponding to the landing push. I cannot agree that the over-driven gear appears to be the sounder engineering job. In my opinion, if the machine and motor are properly designed the under-driven type

makes an entirely compact and substantial job, although a little efficiency may be sacrified due to the churning of the oil.

Mr. H. Marryat (*in reply*): Mr. Higgs has referred to the continuous running lift which I have dealt with in answering Mr. Rawlings in the London discussion. With regard to the experiment in switching on the 21-h.p. motor without starting resistance, the motor did not suffer in any way and the commutator was not damaged as we rather expected it would be, but the contactor switchgear was put out of action. Of course there was a certain amount of main cabling in circuit, and a 300-ampere fuse was not blown. I think that marine thrust bearings were only preferred to ball bearings at a time when the latter were neither so well designed nor made as at present. The question regarding magnetic clutches seems to suggest a continuously running motor. This would be expensive, as the actual running time of a lift is small compared with the standing time. At one time we developed a system of control in which the field of the motor was kept constantly excited, but it was found that the energy consumption of the field with this system exceeded the total consumption of the motor with the usual form of control, in which there is no current passing when the motor is standing.

The chattering referred to by Mr. Mann is more usually the result of bad guide alignment than of brake trouble, and the necessity for frequent adjustment of brake-spring tension indicates that the brake is of insufficient capacity. I would sooner have a large brake with plain wood blocks than a small brake with any patent lining. Where a lining is employed, "Ferodo" or something of a similar nature is most suitable. With regard to single-phase solenoids, when properly designed these may now be relied upon to give good results.

I am in entire agreement with Mr. Harber in his remarks upon American practice. Certainly we should learn all we can of their greater experience, but, bearing in mind that conditions are in many respects different here, I am anxious that we should not continue to accept American figures without query and that we ourselves should make such investigations as are necessary to the design of lifts specially suited for this country. In an endeavour to obtain a more constant rate of acceleration I have tried cutting out the series field in steps, but without any very definite result, or none that I have recorded scientifically. The number of combinations of starting conditions is almost infinite, commencing with the great number of different windings which may be designed for a motor of definite capacity. The regenerative method of control cannot be applied to alternating-current circuits. For high-speed and varying loads upon an a.c. circuit a two- or three-speed motor must be employed and the mechanical brake relied upon to bring the car to floor-level from the low speed. In reply to the question regarding push-button control, when the passenger places his foot upon the floor of the car the landing pushes are cut out of circuit by means of a contact in the car floor, and the car remains under the control of the passenger until he steps out.

ANNUAL DINNER, 1924.

The Annual Dinner of the Institution was held on Thursday, 21st February, 1924, at the Hotel Cecil, when the President, Dr. Alexander Russell, presided over a gathering numbering about 500 persons. Among those present were: The Rt. Hon. the Viscount Chelmsford, P.C., G.C.M.G., G.M.S.I., G.M.I.E., G.B.E. (*First Lord of the Admiralty*), The Rt. Hon. Lord Southborough, P.C., G.C.B., G.C.M.G., G.C.V.O., K.C.S.I. (*Honorary Member*), The Rt. Rev. Bishop H. E. Ryle, K.C.V.O., D.D. (*Dean of Westminster*), The Rt. Hon. Sir Henry Norman, Bart., P.C., Sir George Sutton, Bart., Sir Archibald Denny, Bart., LL.D. (*Chairman, British Engineering Standards Association*), Sir Charles Sherrington, G.B.E., D.Sc. (*President, Royal Society*), Sir Frank Heath, K.C.B. (*Secretary, Department of Scientific and Industrial Research*), Sir Evelyn Murray, K.C.B. (*Secretary, General Post Office*), The Hon. Sir Charles Parsons, K.C.B., F.R.S. (*Hon. Member I.E.E.*, and *President, Institute of Physics*), Sir William Clark, K.C.S.I., C.M.G. (*Comptroller, Overseas Trade Department*), Sir Thomas Holland, K.C.S.I., K.C.I.E., F.R.S. (*Rector, Imperial College of Science and Technology*), Sir John Cadman, K.C.M.G., D.Sc. (*President, Institution of Mining Engineers*), Sir Westcott Abell, K.B.E. (*Chief Ship Surveyor, Lloyd's Register of Shipping*), Sir Arthur Colefax, K.B.E., K.C., Sir James Devonshire, K.B.E. (*Vice-President*), Sir John Dewrance, K.B.E. (*President, Institution of Mechanical Engineers*), Sir Arnold Gridley, K.B.E., Sir William Hale-White, K.B.E., M.D. (*President, Royal Society of Medicine*), Sir Joseph Petavel, K.B.E., D.Sc., F.R.S. (*Director, National Physical Laboratory*), Sir Robert Robertson, K.B.E., F.R.S. (*President, Faraday Society*), Sir Arthur Durrant, C.B.E., M.V.O., (*H.M. Office of Works*), Sir Hugh Thomas, C.B.E., Sir Joseph Broodbank (*President, Institute of Transport*), Sir Harry Haward (*Vice-Chairman, Electricity Commission*), Sir James Kemnal, Sir William Noble, Sir Ernest Rutherford, F.R.S. (*President, British Association*), C. T. Allan (*Chairman, Western Centre*), R. L. Barclay, C.B.E. (*Chairman of Council, London Chamber of Commerce*), J. W. Beauchamp (*Member of Council*), H. Booth, O.B.E. (*Electricity Commissioner*), A. C. Chapman, F.R.S. (*President, Institute of Chemistry*), Commander F. J. Cleary, U.S.N. (*Assistant Naval Attaché, American Embassy*), F. W. Crawter (*Member of Council*), Colonel R. E. B. Crompton, C.B. (*Past President* and *Honorary Member*), R. A. Dalzell, C.B.E. (*Director of Telegraphs and Telephones, G.P.O.*), W. R. Davies, C.B. (*Principal Assistant Secretary, Technical Branch, Board of Education*), Robert W. Dibdin (*President, Incorporated Law Society*), Captain J. M. Donaldson, M.C. (*Member of Council*), D. N. Dunlop (*Member of Council*), Lieut.-Col. K. Edgcumbe (*Member of Council*), Dr. S. Z. de Ferranti (*Past President* and *Faraday Medallist*), Rear-Admiral C. T. M. Fuller, C.B., C.M.G., D.S.O. (*Controller of the Admiralty*), F. Gill (*Past President*), J. A. Gotch (*President, Royal Institute of British Architects*), J. Grosselin (*Past President, Société Française des Electriciens*, and *I.E.E. Local Hon. Secretary for France*), A. F. Harmer (*Member of Council*), A. F. Harrison (*President, Chartered Institute of Secretaries*), J. S. Highfield (*Past President*), H. Hooper (*Hon. Secretary, South Midland Centre*), J. H. Jeans, D.Sc., F.R.S. (*Secretary, Royal Society*), H. H. Jeffcott, Sc.D. (*Secretary, Institution of Civil Engineers*), J. E. Kingsbury, Lieut.-Col. F. A. Cortez Leigh, T.D., R.E. (*Member of Council*), C. D. le Maistre, C.B.E. (*Local Hon. Secretary, American I.E.E.*), B. Longbottom (*Chairman, British Electrical and Allied Manufacturers' Association*), A. B. Mallinson (*Hon. Secretary, North-Western Centre*), C. W. Matthews (*Chairman of Highways Committee, L.C.C.*), S. W. Melsom (*Member of Council*), Lieut.-Col. J. Mitchell Moncrieff, C.B.E. (*Chairman, Association of Consulting Engineers*), W. M. Mordey (*Past President*), J. D. Morgan (*Chairman, South Midland Centre*), A. Page (*Member of Council, I.E.E.*, and *Electricity Commissioner*), G. W. Partridge (*Member of Council*), C. C. Paterson, O.B.E. (*Vice-President*), Colonel T. F. Purves, O.B.E. (*Member of Council, I.E.E.*, and *Engineer-in-Chief, G.P.O.*), W. R. Rawlings (*Member of Councils, I.E.E.* and *Illuminating Engineering Society*), P. Rosling (*Member of Council*), P. F. Rowell (*Secretary*), E. H. Shaughnessy, O.B.E. (*Chairman, Wireless Section*), F. E. Smith, C.B.E., F.R.S. (*President, Physical Society of London*), Roger T. Smith (*Past President*), C. P. Sparks, C.B.E. (*Past President*), A. A. Campbell Swinton, F.R.S. (*Vice-President*), W. J. Turrell, M.D. (*President, Electro-therapeutic Section, Royal Society of Medicine*), O. C. Waygood [*Hon. Secretary, Mersey and North Wales (Liverpool) Centre*], and W. B. Woodhouse (*President, British Electrical Development Association*).

After the usual loyal toasts, the President read the following messages from other societies:

From the French Society of Electricians.

"The French Society of Electricians send most hearty greetings to President Russell, to the Members of Council and to the members of the Institution of Electrical Engineers on the occasion of their Annual Dinner. They are most gratified at the ever-increasing cordial relations between the two Institutions.—ESCHWÈGE, *President.*"

From the American Institute of Electrical Engineers.

"Kindly convey to President and members Institution of Electrical Engineers on occasion their Annual Dinner hearty greetings and best wishes from officers and members.—HARRIS J. RYAN, *President.*"

From the Italian Electrotechnical Association.

"Prof. Ing. G. Sartori, President of the Italian Electrotechnical Association, regrets that, owing to a prior engagement, he is unable to accept Dr. Alexander Russell's kind invitation to the Annual Dinner of the Institution of Electrical Engineers, to be held on the 21st February. He is, however, glad to express his cordial feelings towards the Institution which, in unison with the Italian sister Society, is making noble efforts to achieve scientific results which will do honour to both countries. We send our best wishes to the eminent Institution of Electrical Engineers."

The Rt. Hon. Viscount Chelmsford, P.C., G.C.M.G., G.M.S.I., G.M.I.E., G.B.E. (First Lord of the Admiralty), in proposing the toast of "The Institution of Electrical Engineers," said: "The toast which I have to propose is coupled with the name of the President, a short biographical sketch of whom was sent to me about a week ago, containing the following passage: 'He was born at Ayr in the year 1861, but without this fact being stated anyone who has met him would realize he is of Scotch extraction.' I have been wondering why one would realize that he is of Scotch extraction, and the only thing which has convinced me is that he is sitting in the President's chair. It will be found that Scotsmen generally manage to get into the big offices and the big positions. During my conversation with the President during dinner I have realized how small matters sometimes influence large events. The President tells me that 40 years ago he was competing for a scholarship at Oxford with the present Archbishop of York. While they were at the examination a telegram reached him to the effect that he had been elected to a scholarship at Cambridge. The consequence was that he went to Cambridge instead of to Oxford. One would like to speculate whether, if he had got the scholarship at Oxford, he would have been Archbishop of York? I can say quite confidently that he would not have been President of this Institution. Before I leave the subject of the President, may I add that he has been nominated to-day for a Fellowship of the Royal Society, which is, I suppose, one of the greatest distinctions to which any Englishman can aspire. Now let me turn for a few moments to the toast which I have to propose. I have been long enough at the Admiralty to realize that a modern ship, especially a modern warship, without electricity is almost inconceivable. In every sphere of activity in that ship electricity almost invariably comes in. We must have light; it is electric light. We must have ventilation; it is through electric fans that we get it. We must have communication; again it must be electrical. The control of gunnery, and the firing of modern guns, we can only get by using electricity. There is one other matter to which I should like to allude, because it happens to have been my lot during the short time I have been at the Admiralty to have been engaged in what seems to be that perennial controversy between the Air Ministry and the Admiralty. There is a point in that controversy which is not generally known, I think, but which is very interesting from the point of view of electricity. It is sometimes forgotten that when the Admiralty say that they would like wireless apparatus of their own on the aircraft which are going to play a part in the Fleet air arm, such wireless apparatus in connection with naval operations is of primary importance—of far greater importance than the aeroplane itself—because upon the wireless apparatus depends whether the Fleet Commander is going to get the information that he is expecting from his aircraft. It stands in absolute contradistinction to what happens on land, because the pilot who is working with land forces is always able to land behind his lines and take his messages. No such thing is possible to the naval wireless operator. He has to send his message by wireless or it is not delivered at all. Then, again, take submarines. Unless a submarine had large secondary batteries it would be useless. During the last month I have discovered that there is a development of the potentialities of submarines; there is an anti-submarine department; and as the submarines get ahead in one direction the anti-submarine department gets to know of that direction and immediately proceeds to devise something by which the submarine can be countered. In both departments electricity plays an important part. I could go on, but I think that I have said sufficient to show that the Navy is deeply indebted to electrical engineers for much of its efficiency. At the same time, however, I think that electrical engineers have some cause for indebtedness to the Navy. It is through the increasing requirements and demands of the Navy that electrical engineers are provided, as a profession, with a stimulus to fresh invention and to fresh developments. I ask you to rise and drink with me the toast of 'The Institution of Electrical Engineers,' coupled with the name of your President."

The President, in responding, said: "I am grateful to Lord Chelmsford for having spoken so kindly of our Institution and of our industry, and for having referred so kindly to myself. In Lord Chelmsford we have a Minister who has filled the highest offices of State with distinction and universal acceptance. The activities of the Research Department of the Admiralty are reflected in the equipment of their latest vessels. They have proved that science is a weapon of greater potential value than weight of broadsides. Some of the activities of that Department will prove of value to the mercantile marine; for example, the radio-acoustic method of locating the position of a ship at sea and communicating the result to the ship in a few minutes. This can be done in rough and foggy weather and in all seasons of the year. The method can doubtless be improved. I hope that some of our younger radio engineers will turn their attention from devising new methods of receiving broadcasting to navigation problems which are in urgent need of solution. I feel that it is within our power to devise means whereby a seaman in a cargo boat, or even in a fishing smack, would be enabled to determine his position at sea quickly and easily. Radio first proved its value in navigation. Let us develop it further to lessen the risks of those that go down to the sea in ships, that do business in great waters. The work of our Institution overlaps that of many other Institutions. We cherish feelings of lively gratitude to the Institution of Civil Engineers for their help when we were a young

and struggling society. Now when we are prosperous we are always willing to help and co-operate with other societies. To me it is an especial pleasure that on the 21st March next the Physical Society of London will celebrate its Jubilee in our building. We congratulate it on the excellent work that it is doing for science and, incidentally, for industry. We hope that it will prosper in the future even more than it has done in the past. As electricians we remember that the first polyphase motor was shown in action at a meeting of this Society in June 1879. The crude toy then shown was the forerunner of those large and economic machines which are toiling endlessly for our benefit in coal-pits and factories. We gladly welcome the valuable help which both the Physical Society of London and the American Physical Society are giving us in the production of the Physics Section of *Science Abstracts*, and we are looking forward to greatly extending the usefulness of this well-known publication. We are at the beginning of an almost miraculous linking up of the whole world by the electrical reproduction of sound. The simplicity of this new scientific development is the aspect of it which seems most astounding to the older electricians. The United States of America are brought very close to us when we can listen to speeches being broadcast from New York. Several English amateurs have already succeeded in establishing occasional two-way communication with several American and Canadian amateurs. We are on the eve of many practical applications of radio broadcasting in our schools. The time is rapidly approaching when our railways will be electrified. Amongst our members are many traction engineers and inventors. The transverter of Mr. W. E. Highfield should prove of great value in long-distance electric traction. At the present moment our railways are consuming unnecessarily some 6 million tons of coal per annum. The past year can be looked at with complacency by the supply industry. We have made steady progress. The price of electricity has been reduced. There has been an increase in the demand and a consequent increase in the work of the associated industries. I was pleased to learn last week that the National Association of Supervising Electricians has the names of only three unemployed members in its books. Luckily for manufacturers, existing plant is always depreciating. They recognize, too, that new inventions are continually being made, and they are always on the look-out for improvements. Assuming that this country is to maintain its place in the front rank of civilized nations, new inventions must always be forthcoming. It is of vital importance to the nation that every schoolboy who shows an inventive turn of mind should be encouraged to follow his bent, even if this involve very early specialization. William Thomson (Lord Kelvin) when he was 15 gained a university medal for an essay on the figure of the earth. Dr. Ferranti invented the Ferranti alternator when he was 18. Many have been prevented from specializing at an early age by the necessity of passing many examinations. In my opinion the training requisite for passing examinations does not encourage the inventive faculty. The loss to the nation when an inventive genius is prevented from developing is a grievous one. We are looking forward with lively interest to the World Power Conference at the British Empire Exhibition this year. It will bring together engineers from every civilized country in the world. We are certain that it will work for a better understanding between the nations. Engineering is truly international. The invention of the telephone by Alexander Graham Bell, for instance, was a boon to the whole world. On the 10th and 11th July next we are uniting with the Royal Society and with practically every other scientific and engineering Society in the kingdom in celebrating the centenary of the birth of Lord Kelvin, who was three times our President. To many of the coming generation of engineers he is merely a name. It is right, therefore, that they should be reminded of the great work which he did in advancing science and industry—pioneering work that has proved of such great value in so many different fields. The advance of engineering is never finished; it can never rest; it can never be perfect. This Institution gives us opportunities of service. We strive to carry out the injunction of our Founders to do our utmost to advance electrical science. We are proud of our Institution. We are glad that our work tends to ameliorate the lot of labour in every country. We are ever looking out for ways of making Nature more and more a servant of humanity."

Mr. F. Gill (Past President) then proposed the toast of "Our Guests," to which **Sir William Clark, K.C.S.I., C.M.G.** (Comptroller, Overseas Trade Department), and **Sir Ernest Rutherford, F.R.S.** (President, British Association), responded.

At the invitation of the President, **Colonel R. E. B. Crompton, C.B.** (Past President and Honorary Member), and **Dr. S. Z. de Ferranti** (Past President and Faraday Medallist) also spoke.

A reunion was then held in the Victoria Hall of the hotel.

ATMOSPHERICS AND THEIR EFFECT ON WIRELESS RECEIVERS.

By E. B. Moullin, M.A., Associate Member.

(*Paper first received* 2nd *July, and in final form* 18th *December*, 1923; *read before the* Wireless Section 6th *February*, 1924.

Summary.

The paper contains a mathematical analysis of the effect of an atmospheric upon a wireless receiver. The choice of functions representing the atmospheric has been governed by information contained in *Proceedings of the Royal Society*, A, vol. 103. The effect of each of several wave-forms is calculated and the results are compared. The effect is calculated of an atmospheric acting respectively on a tuned antenna, on an aperiodic antenna, on a tuned loop aerial, and also the combination of each of these with a selective amplifier. In each case a formula is derived which gives the ratio of signal to atmospheric, and it is shown that for a given wave-length these formulæ are identical. The possible advantage to be got from the use of an aperiodic antenna or of a slightly distuned periodic circuit is considered in detail. Finally, the rectified current produced by the atmospheric is compared with that produced by the signal, and it is shown that the decrement of the aerial should always be reduced to the point where ringing or bad shaping of signals commences.

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Index to the Formulæ Derived in the Paper.

1. Introduction.

The paper on the "Nature of Atmospherics" which has been published recently by the Royal Society* contains information which makes it possible to analyse mathematically the effect of an atmospheric on a wireless receiver.† The authors of that paper used a cathode-ray oscillograph of the pattern made by the Western Electric Company; they have recorded many oscillograms of atmospherics and have measured both their amplitude and duration. The oscillograms show that the average duration of an atmospheric is about 1/500th second and that the period of growth usually equals, and is seldom less than half, the time of decay. The average value of the maximum field strength of the atmospherics observed was about 0·1 V per metre, which is about 5 000 times the field strength of average wireless signals.

In the past it has been assumed that an atmospheric rises to its maximum in an indefinitely short period of time and decays at a rate such that it has sensibly died out in a time which is short compared with the duration of a Morse dot (at 25 words per minute a Morse dot lasts about 1/20th second).

* See R. A. Watson Watt and E. V. Appleton: *Proceedings of the Royal Society*, A, 1923, vol. 103.

† So far as the author is aware, no analysis has been made of the effect of an atmospheric, except an incorrect one by M. Abraham. (See *Jahrbuch der Drahtlose Telegraphie*, 1919, vol. 14, p. 259, and a correction by Friis and Sivian, *Wireless World and Radio Review*, 1921, vol. 2, p. 526.)

The mathematical analysis to be described in this paper has been made in order to discover if disturbance by atmospherics can be reduced appreciably by suitable design of ordinary receiving circuits. The analysis shows where and when it is advisable to reduce the decrement of a circuit by the use of retroaction; it also shows that an atmospheric is relatively ineffectual in setting up oscillations in the receiver, and so helps to explain why signals have been able to hold their own against atmospherics that are several thousand times as strong. The use of special devices such as balanced aerials or current limiters is not considered.

2. Wave-form of the Atmospheric.

Watt and Appleton found that the commonest wave-forms were approximately those shown in Fig. 1 (*a*),

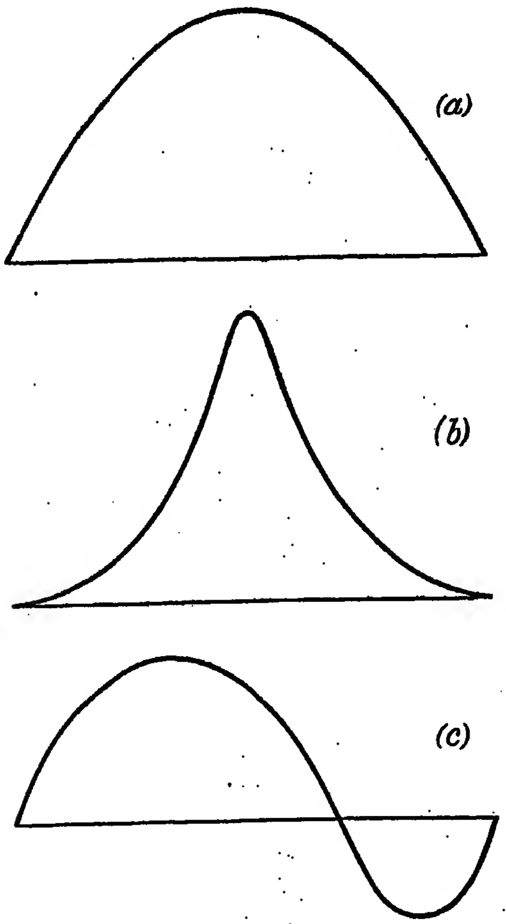

Fig. 1.

(*b*) and (*c*). About one-third of the observed wave-forms closely resembled type (*a*), and about one-third type (*c*). The remaining third resembled type (*b*) or a modification of type (*c*) in which one half-wave was peaked and the second half-wave rounded. Two-thirds of those resembling (*a*) were accurately symmetrical, and 90 per cent had a time of growth which was not less than half the time of decay. Type (*b*) were less markedly symmetrical than type (*a*). The atmospherics of type (*c*), which roughly resemble a heavily damped sine wave, are normally characterized by the half-wave of greater amplitude lasting about $1\frac{3}{4}$ times as long as the smaller half-wave. The majority of type (*c*) showed two half-waves only, but about 8 per cent showed three, and 2 per cent showed eight, half-waves. The authors point out that since successive half-waves seldom occupy the same time, and since succeeding half-waves may differ appreciably in form, it is a very poor approximation to represent an atmospheric by any simple function such as $A\epsilon^{-bt}\sin pt$.

If we were investigating the rate of change of the electric moment of the thundercloud from which the disturbance originates, no doubt that would be so, but for investigating the effect that the discharge has on a wireless receiver we shall show that the simple approximation represents the problem very closely. The mathematical analysis shows that the harmful effect depends mainly on the time of duration of the first half-wave and its initial rate of increase. Various functions are taken to represent the atmospheric, and it is shown that in each case the effect produced is approximately the same as would have been produced by a simple heavily-damped sine wave of the same initial maximum value.

Having established the fact that the simple expression $A\epsilon^{-bt}\sin pt$ represents the actual conditions with considerable accuracy, the function $e = A\epsilon^{-\frac{1}{2}pt}\sin pt$ has been chosen to represent the standard atmospheric. This function is delineated in Fig. 2, and it is seen that the maximum of the third half-wave is only about 4 per cent of the first wave. The damped sine curve has been adopted because it is the function which leads to the simplest mathematical treatment; also, if an atmospheric was of that form it would produce rather greater disturbance than any of the actual forms observed by Watt and Appleton.

By measurement of the period of duration of the

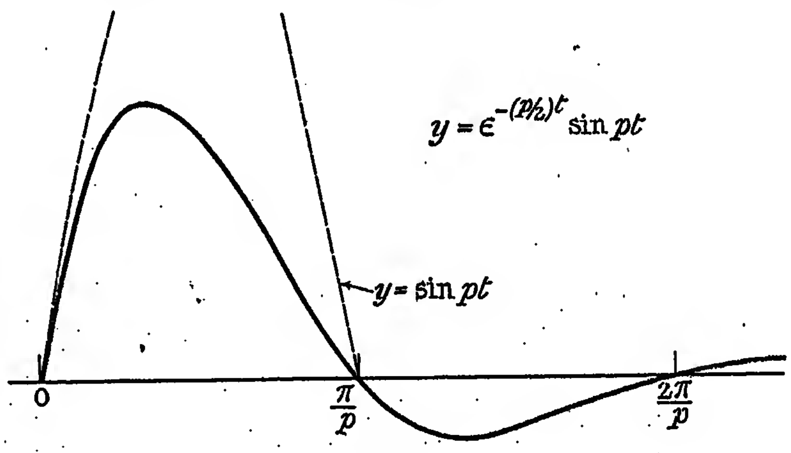

Fig. 2.

longer half-wave Watt and Appleton state (*ibid.*) that the mean value of p is about $3 \cdot 6 \times 10^3$. Representing a steady continuous-wave signal by the function $e = E\sin\omega t$, the appropriate value of ω corresponding to a wave-length of 6 000 m is $3 \cdot 1 \times 10^5$ and corresponding to 600 m is $3 \cdot 1 \times 10^6$. For the band of wave-lengths included between 600 m and 6 000 m we have a value for ω/p which lies between, say, 100 and 1 000.

3. Functions used to Approximate to the Form of Atmospherics.

As stated previously, the most frequent form of aperiodic atmospheric is the symmetrical rounded hump. To represent this it has been assumed that the form of the atmospheric was $e = A\sin pt$, starting at time $t = 0$ and ending abruptly at time $t = \pi/p$. To represent the type shown in Fig. 1 (*b*) it has been assumed that

the atmospheric was of the form $e = A \sin pt - B \sin 3pt$, starting at time $t = 0$ and ending abruptly at time $t = \pi/p$. It may be noted that if this function is used to represent type (b), then the greatest value that the coefficient B can have is $A/3$. If B exceeds $A/3$ then a negative loop is formed within the span of a half-wave of the fundamental, as shown in Fig. 3, which depicts the function $e = A (\sin pt - \sin 3pt)$.

If we imagine that an atmospheric having the form of this function does not affect the receiver until after time $t = \pi/4p$, and ends abruptly at time $t = \pi/p$, we have a close approximation to type (c), for the larger half-wave lasts twice as long as the second half-wave.

The concept of a single half sine wave of E.M.F.

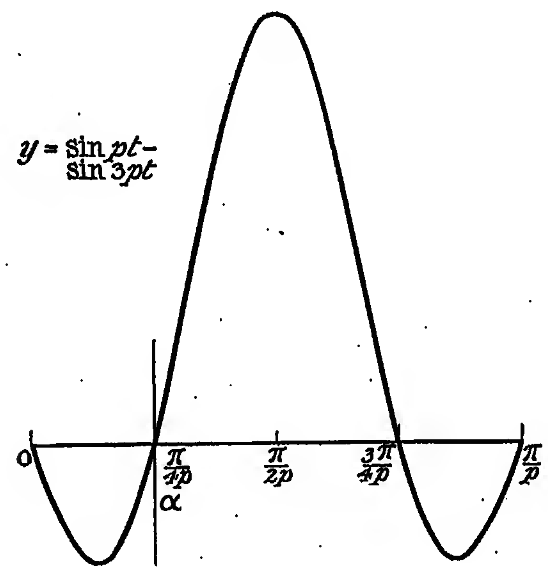

FIG. 3.

acting on a receiver could be realized, for we can imagine that it emanates from a spark transmitter in which the spark gap, placed direct in the antenna circuit, is arranged to quench the oscillation at the instant when the current falls to zero for the first time.

4. Current produced by an Atmospheric Acting on an Open Antenna.

If a receiver is actuated by an open antenna the E.M.F. induced in it will have the same wave-form as the atmospheric. If reception is by means of a coil aerial then the E.M.F. induced in it will not have the same wave-form as the atmospheric, for the E.M.F. depends on the rate of change of flux through the coil. At present, consideration is limited to the open antenna, and the coil is considered in Section 7 below.

Let the antenna of capacity C have an inductance L placed in series with it, the value of L being such as to tune the antenna to a frequency which is considerably less than its natural frequency when unloaded. Let the total effective resistance of the circuit be R, and let the logarithmic decrement of the circuit at that frequency be δ.

It is convenient to resolve the current produced by the atmospheric into two components, one having the same frequency and wave-form as the atmospheric and corresponding to the particular integral of the differential equation, and the other corresponding to the complementary function of the differential equation. The latter component is a simple damped sine wave having the same frequency as that to which the antenna is tuned. Since the particular integral has the same form as the atmospheric it has a period which is much greater than the complementary function, for (see Section 2) ω/p has some value which lies between, say, 100 and 1 000. For convenience we shall call the particular integral the low-frequency portion of the current, and the complementary function the high-frequency portion of the current. In Section 5 we shall see that the low-frequency portion is important only because it fixes the size of the high-frequency portion.

The P.D. (applied to the amplifier or rectifier) produced by the low-frequency portion is always negligible in comparison with that produced by the high-frequency portion.

It will be assumed that the appropriate circuit representing the loaded antenna is as shown in Fig. 4. Consequently, the differential equations representing the flow of current are :—

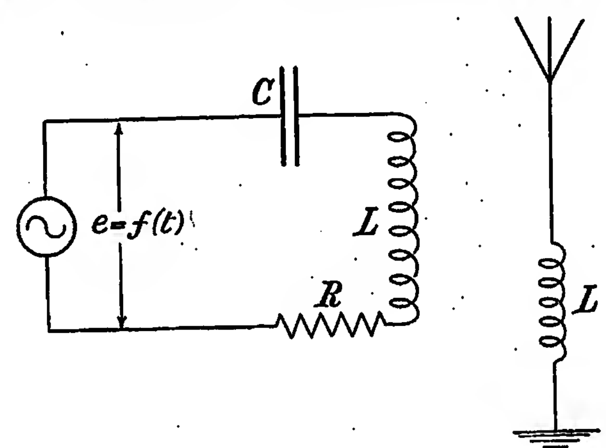

FIG. 4.

$[D^2 + (R/L)D + \omega^2]i = 0$ for times less than zero.
$[D^2 + (R/L)D + \omega^2]i = 1/L\, f'(t)$ for times between 0 and t'.
$[D^2 + (R/L)D + \omega^2]i = 0$ for all times greater than t'.

The third equation is required only when we are considering an atmospheric which ends abruptly at time t', as, for instance, a single half sine curve. If the atmospheric is represented by a simple heavily-damped sine curve then t' is infinite, and the third equation is not required. For an open antenna, $f(t)$ is of the same form as the atmospheric. If the atmospheric is represented by a function such as $e = E\epsilon^{-bt} \sin pt$, where E is expressed in terms of the potential gradient of the electric field, then $f(t)$ is given by $e = hE\epsilon^{-bt} \sin pt$, where h is the effective height of the receiving antenna. It is inconvenient to separate h and E, and this product will be written A, so that the E.M.F. set up in the antenna is given by $e = A\epsilon^{-bt} \sin pt$ or $e = A \sin pt$ or $e = A \sin pt - B \sin 3pt$, according to circumstances.

First we will determine the low-frequency current produced by the atmospheric of the form $e = A\epsilon^{-bt} \sin pt$, where $b \doteq p/2$. We have

$$\left(D^2 + \frac{R}{L}D + \omega^2\right)i = \frac{A}{L}\epsilon^{-bt}(-b \sin pt + p \cos pt)$$

whence

$$i = \frac{A\epsilon^{-bt}}{L} \times \frac{(-b\sin pt + p\cos pt)}{D(R/L - 2b) + (b^2 - p^2 - bR/L + \omega^2)}$$
(with $D^2 = -p^2$)

$$\doteqdot \frac{A\epsilon^{-bt}}{L} \times \frac{(-b\sin pt + p\cos pt)}{D(R/L - 2b) + \omega^2} \quad \text{because } \omega >>> p$$

$$\doteqdot -\frac{AC\epsilon^{-bt}}{\omega^2}\left\{\left(\omega^2 b - p^2\frac{R}{L} - 2b\right)\sin pt - \left(\omega^2 p + bp\frac{R}{L} - 2b\right)\cos pt\right\}$$

$$\doteqdot ACp\epsilon^{-bt}[\cos pt - (b/p)\sin pt]$$

Hence, as might be expected, to the low frequency of the atmospheric the circuit behaves as if it were simply a capacity C.

Similarly, if the atmospheric is $e = A\sin pt - B\sin 3pt$, the low-frequency current is given by

$$i \doteqdot pC(A\cos pt - 3B\cos 3pt)$$

To approximate to the type of atmospheric shown in Fig. 1 (c), the value of B lies between zero and $\frac{1}{3}A$, and to represent the type shown in Fig. 1(b) the appropriate value of B lies between $\frac{1}{3}A$ and A. For values of B between these limits we shall imagine that the atmospheric begins to act on the antenna at the instant when it passes through the value zero after having passed its first maximum (see point a in Fig. 3).

In every case the high-frequency portion of the current produced by the atmospheric will be of the form

$$i = K\epsilon^{-mt}\sin\omega t + M\epsilon^{-mt}\cos\omega t$$

where m is the damping factor proper to the circuit LRC; K and M are arbitrary constants.

The complete solution of the differential equation is obtained by adding together the high-frequency and low-frequency terms. The appropriate values of K and M are determined from the condition that in the complete solution both i and di/dt are zero when t is zero.

Thus in the case of an atmospheric of the form $e = A\epsilon^{-bt}\sin pt$ we have

$$i = K\epsilon^{-mt}\sin\omega t + M\epsilon^{-mt}\cos\omega t + ApC\epsilon^{-bt}[\cos pt - (b/p)\sin pt] \quad (1)$$

$$\text{and } \frac{di}{dt} = K\epsilon^{-mt}(-m\sin\omega t + \omega\cos\omega t) + M\epsilon^{-mt}(-m\cos\omega t - \omega\sin\omega t) + ApC\epsilon^{-bt}[-b\cos pt - p\sin pt + (b^2/p)\sin pt - b\cos pt]$$

Now, when $t = 0$, both i and $\frac{di}{dt}$ are zero.

Therefore $M = -ApC$ and $\omega K - mM - 2ApCb = 0$
Therefore $K = M/\omega(m - 2b)$

$$\doteqdot (p/\omega)M\left(-1 + \frac{\omega}{p} \times \frac{\delta}{2\pi}\right) \text{ since } b \doteqdot p/2$$

where δ is the decrement of the LRC circuit.

It will be seen later that it is important to reduce δ to the lowest possible value consistent with stability or signalling speed. Suppose, for example, that $\delta = 0\cdot01$ and that $\omega/p = 100$. Then

$$K \doteqdot (p/\omega)M \doteqdot 0\cdot01M, \text{ and hence } M >>> K$$

Thus to a very close approximation the high-frequency current may be represented by the expression:

$$i = -ApC\epsilon^{-mt}\cos\omega t$$

With atmospherics taking the form of undamped sinusoids, ending abruptly, we must consider two high-frequency terms, commencing at the start and at the abrupt end respectively of the atmospheric. For the initial high-frequency term we have

$$i = K\epsilon^{-mt}\sin\omega t + M\epsilon^{-mt}\cos\omega t + ApC\cos pt - 3BpC\cos 3pt$$

If B is less than $\frac{1}{3}A$ we consider that $i = 0$ when $t = 0$, and if B is equal to A we shall consider that the atmospheric begins to act when $t = \pi/(4p)$.

Hence $M = -pC(A - 3B)$ (if $i = 0$ when $t = 0$)
or $M = -pCA \times 2\sqrt{2}$ [if $i = 0$ when $t = \pi/(4p)$]

It can be shown that in either case $M >>> K$.

The high-frequency currents set up by the various forms of atmospheric are readily compared by means of Table 1.

TABLE 1.

Form of atmospheric	High-frequency current set up
$e = A\epsilon^{-bt}\sin pt$	$i = -ApC\epsilon^{-mt}\cos\omega t$
$e = A\sin pt$	$i = -ApC\epsilon^{-mt}\cos\omega t$
$e = A\sin pt - (A/3)\sin 3pt$	$i = 0$
$e = A\sin pt - A\sin 3pt$	$i = -2\sqrt{2}ApC\epsilon^{-mt}\cos\omega t$

It is interesting to note that should the atmospheric be of the form $A\sin pt - \frac{A}{3}\sin 3pt$, no high-frequency current is set up, and consequently such an atmospheric would be sensibly innocuous.

Now on reference to the above table it will be seen that in each case the high-frequency current is proportional to the initial rate of increase of the atmospheric E.M.F. An atmospheric having initial and final slopes equal to zero will not create any sensible disturbance in a lightly damped LRC circuit.

Table 1 must not be used to estimate which form of atmospheric will create the greatest disturbance; such a comparison must be made between atmospherics which actually attain the same maximum value.

Table 2 has been arranged to facilitate this comparison.

Hence, so far as the initial high-frequency current is concerned, that produced by the damped sinusoid has the greatest value, because such an atmospheric has the same initial slope as an undamped sine curve of about twice the amplitude.

If the atmospheric is represented by an undamped sinusoidal function ending abruptly at time $t = \pi/p$, we have another current set up at the abrupt ending.

Hence, if $t > 0 < \pi/p$

$$i_1 = ApC[-\epsilon^{-mt}\cos\omega t + \cos pt - (3B/A)\cos 3pt]$$

and for values of t greater than π/p

$$i_2 = \alpha\epsilon^{-mt}\cos\omega t + \beta\epsilon^{-mt}\sin\omega t$$

α and β are determined by making the values of i_1 and di_1/dt obtaining at time $t = \pi/p$ agree with the values of i_2 and di_2/dt when $t = 0$.

If we assume that the value of δ is such that $\omega\delta/p \doteqdot 1$, and if $\cos(\omega\pi/p) = -1$, then it is easy to show that

$$i_2 = -1\cdot 6ApC\epsilon^{-mt}\cos(\omega t + \lambda)$$

If $\cos(\omega\pi/p)$ has any value other than 1 the resulting current will be smaller than the value given above.

Hence, in comparison with a damped sinusoid which gives a current $-\frac{1}{2}DpC\epsilon^{-mt}\cos\omega t$, a single half sine curve gives a current $-\frac{1}{2}DpC\epsilon^{-mt}\cos\omega t$, which, if $\delta = 0\cdot 01$, will persist until its amplitude has fallen by about 40 per cent, and is then followed by another current which may have a value equal to $i_2 = 0\cdot 4DpC\epsilon^{-mt}\cos\omega t$ in the worst possible case. Hence it appears that for a given maximum value either form of atmospheric just considered will have approximately the same effect, and it seems possible that the simple heavily-damped sine curve may represent the worst case.

Hence it seems reasonable to adopt the form $e = A\epsilon^{-bt}\sin pt$ (where $b \doteqdot \frac{1}{2}p$) as the standard atmospheric for purposes of investigation. This function leads to the simplest analysis, since only one train of oscillations has to be considered.

5. The Effect of the Atmospheric on Apparatus or Circuits Coupled to the Antenna.

In the following section it is presumed that a triode valve is coupled directly across the aerial tuning inductance; and this valve is presumed to be either a rectifier, or the first valve of a chain of selective amplifiers actuating a rectifier. It is supposed that it is possible, by means of retroaction, to reduce the decrement of the antenna to any required degree, and if necessary that of all of the selective amplifiers also.

The P.D. impressed upon the first valve is the P.D. developed across the ends of the aerial tuning inductance by the passage through it of the current set up by the atmospheric. Thus if the current in the aerial be i at any instant, then at any instant the P.D. applied to the first valve is $L\frac{di}{dt}$.

It follows from formula (1) that

$$L\frac{di}{dt} = LApC\Big\{\epsilon^{-\frac{1}{2}pt}\Big(-\frac{p}{2}\cos pt - p\sin pt + \tfrac{1}{4}p\sin pt - \tfrac{1}{2}p\cos pt\Big) - \epsilon^{-mt}(-\omega\sin\omega t - m\cos\omega t)\Big\}$$

$$\doteqdot -1\cdot 12A\frac{p^2}{\omega^2}\epsilon^{-\frac{1}{2}pt}\sin(pt+\lambda) + A\frac{p}{\omega}\epsilon^{-mt}\sin\omega t \quad (2)$$

when $b \doteqdot \frac{p}{2}$ and $\omega >> p$.

It is interesting to notice that neither L nor C appears explicitly in either the low-frequency or the high-frequency component of this expression. Hence for antennæ of the same effective height and decrement and tuned to the same wave-length the P.D. produced by the atmospheric is independent of the capacity of the antenna and depends only on the ratio of the signal frequency to the atmospheric frequency.

The ratio of the high-frequency component to the low-frequency component is given by

$$\frac{\text{High-frequency P.D.}}{\text{Low-frequency P.D.}} = \frac{(\omega/p)\epsilon^{-mt}\sin\omega t}{1\cdot 2\,\epsilon^{-\frac{1}{2}pt}\sin(pt+\lambda)}$$

The minimum value of this ratio is approximately equal to $(\omega/p)\sin\omega t$; when $\frac{\omega}{p} >> 1$ and $\delta << 1$.

Hence the low-frequency P.D. is vastly smaller than the high-frequency P.D. and is negligible in comparison. If the combined P.D. is applied to a selective amplifier the high-frequency component will be amplified and the low-frequency component will be diminished, so that each successive stage of high-frequency amplification makes the low-frequency component of less and less importance.

At this stage it may be of interest to consider probable numerical values for these two components. We shall suppose that an antenna, which is tuned to a wave-length of 6 000 m, has an effective height of 30 m. The field strength of the atmospheric is 0·1 volt per metre at its maximum, so that the maximum E.M.F. in the antenna is 3 V, and the appropriate value of A in formula (2) will be about 6 V. Since p/ω is about 1/100, the initial amplitude of the high-frequency component will be about 60 mV and the maximum of the low-frequency component will be about 0·8 mV.

Table 2.

Form of atmospheric	Maximum amplitude attained	High-frequency current set up by atmospherics each of which rises to the same maximum, D
$e = A\epsilon^{-\frac{1}{2}pt}\sin pt$	$\frac{1}{2}A$	$i = -\frac{1}{2}DpC\epsilon^{-mt}\cos\omega t$
$e = A\sin pt$	A	$i = -\frac{1}{2}DpC\epsilon^{-mt}\cos\omega t$
$e = A\sin pt - (A/3)\sin 3pt$	$\frac{4}{3}A$	$i = 0$
$e = A\sin pt - A\sin 3pt$	$2A$	$i = -\frac{1}{2\sqrt{2}}DpC\epsilon^{-mt}\cos\omega t$

The important point to consider, however, is not the absolute value of the P.D. set up by the atmospheric, but the ratio between the atmospheric and the signal. The P.D. produced by a sustained continuous-wave signal $e = E \sin \omega t$ to which the antenna is tuned is given by the expression

$$v = E\frac{\pi}{\delta} \cos \omega t$$

So that the ratio of signal to atmospheric is given by

$$\frac{\text{Signal P.D.}}{\text{Atmospheric P.D.}} = \frac{E\pi \cos \omega t}{\delta(p/\omega)A\epsilon^{mt} \sin \omega t} \quad . \quad (3)$$

Consequently the ratio of signal P.D. to initial maximum P.D. of atmospheric is equal to $\frac{E\pi\omega}{A\delta p}$. It is seen that for fixed conditions of signal strength and wave-length this ratio increases in direct proportion as the aerial decrement is reduced; hence to minimize the disturbances caused by atmospherics the aerial decrement should be reduced to the lowest value compatible with stability and speed of signalling. The physical explanation is that whereas the signal P.D. increases in inverse proportion to the aerial decrement, the initial maximum of the atmospheric P.D. is sensibly independent of the aerial decrement, see formula (2). It will be seen in Section 8 that it is not equally effective to apply the retroaction in the amplifier circuit; in fact it is deleterious to reduce the decrement of the amplifier below that of the aerial. So it seems important to apply the retroaction in the first oscillatory circuit.

It is interesting to investigate the relative value of the field strength of the signal and atmospheric which will give the same maximum P.D. across the aerial tuning inductance. Suppose that for various reasons δ is limited to about 0·003, then if $E\pi\omega$ is to be equal to $A\delta p$, E will be approximately equal to $(\omega A/100p)$. If the signal wave-length is 6 000 m, then p/ω is about 0·01, and consequently for equality of maximum P.D. we have $A = 10^6 E$. Now, as pointed out in Table 2, the maximum value of the field strength of the atmospheric is about $\frac{1}{2}A$, and (as stated in Section 1) Watt and Appleton find that the average value of $\frac{1}{2}A$ is about 0·1 volt per metre. Hence by sufficient reduction of the antenna decrement it would appear that E may be reduced to a few microvolts per metre and yet be sufficiently strong to hold its own against the atmospherics ordinarily to be expected in this country. That comparatively strong atmospherics are relatively very ineffectual in causing a disturbance is, after all, a matter of common experience rather than of surprise, for had it been otherwise it is improbable that wireless telegraphy would ever have emerged from its experimental stages, and continuous long-distance services would have been impossible.

6. Current produced by an Atmospheric in an Aperiodic Antenna.

At the present time it is fairly common to use aperiodic antennæ for reception. The term "aperiodic antenna" is used to describe an aerial circuit which contains no added inductance and the resistance of which is at least of such a value as to render a discharge non-oscillatory. With such a circuit the necessary resistance is usually added at the base of the antenna, and its ends are connected to the terminals of a selective amplifier. All necessary tuning is then performed in the circuits of the amplifiers. Such a circuit is shown in Fig. 5. This system of reception has been proposed* and used experimentally to make multiplex reception possible on a single antenna and has also been employed in the hope of minimizing atmospheric disturbances.

The effect of the standard atmospheric acting on the circuit of Fig. 5 will now be considered. It is clear that if the value of R is indefinitely great, the P.D. applied between the terminals of the amplifier will be sensible equal to the E.M.F. of both signal and atmospheric. However, since the frequency of the signal is likely to be at least a hundred times as great as the frequency of the atmospheric, it is possible to arrange the value of R so that while the P.D. developed across

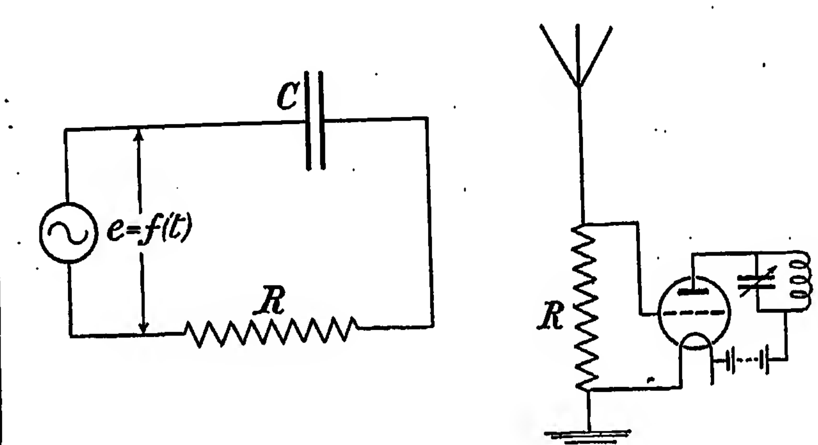

Fig. 5.

it by the signal is sensibly equal to the signal E.M.F., the P.D. developed by the atmospheric is only a small portion of the atmospheric E.M.F. In this way some degree of discrimination between signals and atmospherics can be obtained. In short, for an atmospheric the antenna acts like a simple capacity, and to the signal like a simple resistance.

The differential equation expressing the current produced by the atmospheric $e = A\epsilon^{-bt} \sin pt$ (where b is approximately equal to $\frac{1}{2}p$) is

$$\left(D + \frac{1}{RC}\right)i = \frac{A}{R}\epsilon^{-bt}(-b \sin pt + p \cos pt)$$

The approximate solution of this equation for the case where $1/(RC)$ is much greater than p is given by

$$i = -ApC\left\{\epsilon^{-\frac{1}{RC}t} - \epsilon^{-bt}[\cos pt - (b/p) \sin pt]\right\} \quad (4)$$

Writing $RC = x/\omega$ (where x is, say, not less than about 3), the P.D. developed across R is given by

$$v = -\frac{xAp}{\omega}\left\{\epsilon^{-\frac{\omega}{x}t} - \epsilon^{-bt}[\cos pt - (b/p) \sin pt]\right\} \quad (5)$$

* See L. B. Turner, British Specification No. 189 693.

The P.D. across R produced by the signal $e = E \sin \omega t$, is given by the expression

$$v \doteq E\left(1 - \frac{1}{2x^2} + \frac{1}{8x^4}\right) \sin \omega t$$

Now, so long as x is greater than, say, 3, the signal P.D. is nearly independent of x, but the atmospheric P.D. increases greatly with x. If x has the value 3, and if $\omega = 100p$, then about 1/30th part of the atmospheric E.M.F. is applied to the amplifier.

But using the expression given in formula (5) it can be shown that the initial rate of increase is independent of the value of RC, and, as has been already pointed out (see Section 4), the amplitude of the high-frequency current set up in the first oscillatory circuit depends on this initial rate of increase. Hence so long as the value of R is small enough to make the antenna behave to the atmospheric in sensibly the same manner as if it was a simple capacity, then the exact value of R is unimportant. This subject will be dealt with more fully in Section 10.

It is of interest to calculate a suitable value for R in a specific numerical case. Suppose, for example, that the capacity of the antenna is 1 000 $\mu\mu$F, and that the wave-length of the signals to be received is 6 000 m. If we choose R so that $1/(RC)$ is equal to $\frac{1}{3}\omega$, then its value will be about 10 000 ohms; probably any value of R between, say, 5 000 and 50 000 ohms would be equally suitable. In practice it is common to use values of R which are very much greater than those just calculated, but for minimizing atmospheric disturbances this practice does not seem to be a good one.

7. Current produced by an Atmospheric acting on a Tuned Loop Aerial.

It is commonly believed that where atmospheric disturbance is considerable it is advantageous to receive on a loop rather than on an open antenna. No doubt the advantage can be partly explained by the directional properties of a loop, but analysis shows that quite apart from this a loop has an advantage over an antenna.

In calculating the E.M.F. set up in a loop it is simpler to consider the rate of change of magnetic flux through the loop rather than the line integral round it of the electric field. If at any specified point the electric field set up by the atmospheric is represented by $e = E\epsilon^{-bt} \sin pt$, then the magnetic field can be represented by $h = H\epsilon^{-bt} \sin pt$. If the electric field is measured in volts per cm and the magnetic field in C.G.S. units, then E and H are connected by the relation $E = 300H$.

Let the loop, the dimensions of which are very small compared with the wave-length of the atmospheric, have N turns each of area A, then at any instant the magnetic flux through the loop is given by the expression $\phi = ANh$.

Hence the E.M.F. round the loop is given by the equation

$$e = -\frac{d\phi}{dt} = -NA\frac{dh}{dt} = -ANH\epsilon^{-bt}(-b \sin pt + p \cos pt) \quad (6)$$

Let the loop have inductance L and resistance R, and let it be joined in series with a condenser of capacity C. It is supposed that the value of C has been adjusted so that the circuit is in resonance with a signal E.M.F. $e = E \sin \omega t$.

The differential equation expressing the current set up in the loop is

$$\left(D^2 + \frac{R}{L}D + \omega^2\right)i$$
$$= -\frac{ANH}{L}\epsilon^{-bt}\left\{(b^2 - p^2) \sin pt - 2bp \cos pt\right\}$$

For the case where b and p are both much smaller than ω the approximate solution is given by

$$i = -ANHC\epsilon^{-bt}\left\{(b^2 - p^2) \sin pt - 2bp \cos pt\right\}$$

Thus, as in the case of the antenna, to the low frequency of the atmospheric the loop behaves as a simple capacity C.

The complete solution of the equation will consequently be of the form

$$i = B\epsilon^{-mt} \sin \omega t + D\epsilon^{-mt} \cos \omega t$$
$$- ANHC\epsilon^{-bt}\left\{(b^2 - p^2) \sin pt - 2bp \cos pt\right\}$$

where the constants B and D are determined by the condition that both i and di/dt are zero when t is zero.

Applying these conditions it is readily shown that $D = -2bpCANH$, and that $B \doteq (p/\omega)(D/4)$.

The approximate solution of the high-frequency portion of the current set up in the loop is accordingly given by the expression

$$i = -2bpCANH\epsilon^{-mt} \cos \omega t \quad . \quad . \quad . \quad (7)$$

and the P.D. across the terminals of the loop is given by

$$L\frac{di}{dt} = -2bpCLANH\epsilon^{-mt}(-m \cos \omega t - \omega \sin \omega t)$$
$$\doteq 2b\frac{p}{\omega}ANH\epsilon^{-mt} \sin \omega t \quad . \quad (8)$$

If the magnetic field of a signal is $h' = H' \sin \omega t$, the P.D. between the terminals of the loop is given by

$$L\frac{di}{dt} = ANH'\frac{\pi\omega}{\delta} \sin \omega t$$

Consequently the ratio of signal to atmospheric is given by

$$\frac{\text{Signal}}{\text{Atmospheric}} = \frac{H'\pi\omega^2}{H2\delta bp}$$
$$\doteq \frac{H'\pi\omega^2}{H\delta p^2} \quad (\text{since } b \doteq \tfrac{1}{2}p) \quad . \quad (9)$$

It is instructive to compare this expression with the corresponding one for a tuned antenna [see Section 4, formula (3)] which is

$$\frac{\text{Signal}}{\text{Atmospheric}} = \frac{E\pi\omega}{A\delta p}$$

It is seen that both expressions vary inversely as the decrement of the circuit (loop or antenna), but in the case of the loop the ratio depends on ω^2/p^2 instead of

ω/p for the antenna, and it is evidently from this factor that the loop gains its superiority.

8. Effect of an Atmospheric on a Selective Amplifier Coupled to the Aerial.

The term "selective amplifier" is used to denote an amplifier in which the anode circuit presents an appreciable impedance to currents of one frequency only. One example of such an amplifier may be obtained by placing a lightly-damped tuned stopper circuit between plate and filament. Such an amplifier, connected to the antenna, is shown in Fig. 6. The P.D. developed across

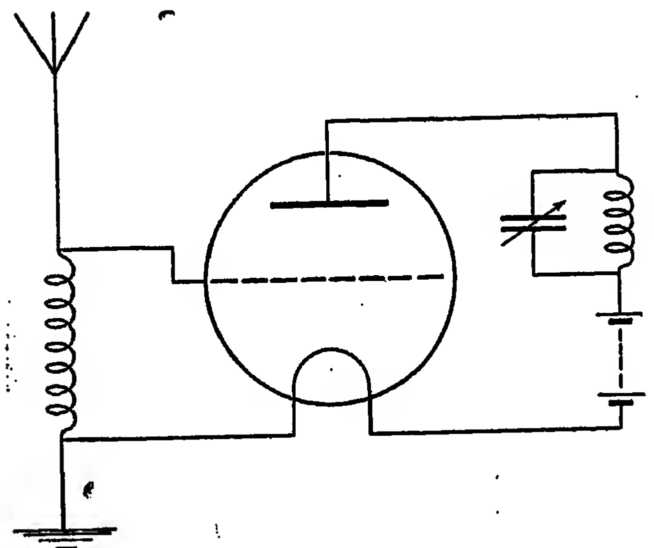

Fig. 6.

the terminals of the anode-circuit impedance is supposed to be handed on in the usual manner to the next triode, which may be another amplifier or a rectifier.

The P.D. applied to the input terminals of the first valve consists of a high-frequency and low-frequency component [see Section 5, formula (2)]. This P.D. will produce a current in the anode-circuit inductance L which will consist of three components, one low-

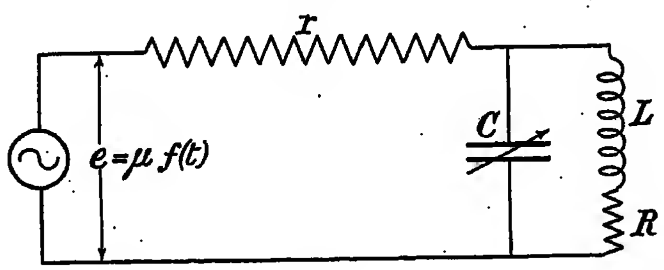

Fig. 7.

frequency and two high-frequency. The two high-frequency components will have the same frequency, since the amplifier is supposed to be tuned to the same frequency as the aerial; one component will have the decrement of the aerial and the other the decrement of the LRC circuit of the amplifier together with the conductance of the valve.

The circuit of the amplifier can be replaced by the equivalent circuit shown in Fig. 7. The input voltage to the equivalent circuit must be represented by μ times the input voltage to the amplifier, where μ is the amplification factor of the valve. The resistance r represents the apparent resistance of the valve and is numerically equal to $1/a$, where a is the anode slope conductance. For ordinary receiving triodes will be between, say, 30 000 and 40 000 ohms.

It is obvious that to the low-frequency component of the applied P.D. the circuit of Fig. 7 will behave in sensibly the same manner as a simple resistance r; that such is actually the case can readily be shown. Hence the low-frequency component of the applied P.D. will produce a current in L which is given by

$$i = -\frac{\mu A p^2}{r\omega^2}\epsilon^{-bt}\left(\tfrac{3}{4}\sin pt + \cos pt\right) \quad . \quad . \quad (10)$$

and the P.D. developed across L by this current is given by

$$L\frac{di}{dt} = -\frac{\mu A p^2}{r\omega^2}pL\epsilon^{-bt}\left(-\tfrac{11}{8}\sin pt + \tfrac{1}{4}\cos pt\right)$$

$$\doteqdot \frac{\mu A p^2}{r\omega^2}pL\epsilon^{-bt}\sin pt \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Now if $p/\omega \doteqdot 1/100$, $\mu = 10$ and $L \doteqdot 4 \times 10^3 \mu H$.

Then $$L\frac{di}{dt} \doteqdot \frac{A}{10^6}\epsilon^{-bt}\sin pt$$

Hence of the E.M.F. in the aerial about one-millionth part will be applied to the second valve. In the numerical case considered in Section 5 this would be about $0{\cdot}8\ \mu V$.

It is now necessary to consider the current produced in L by the high-frequency P.D., $e = \frac{\mu A p}{\omega}\epsilon^{-mt}\sin \omega t$, applied at the terminals of the equivalent circuit.

It is readily shown that the appropriate differential equation expressing this current is given by

$$\left\{D^2 + \left(\frac{R}{L} + \frac{1}{rC}\right)D + \omega^2\right\}i = \frac{\mu A p \omega}{r}\epsilon^{-mt}\sin \omega t$$
$$\equiv K'\epsilon^{-mt}\sin \omega t$$

whence it follows that

$$i = K'\epsilon^{-mt}\frac{\sin \omega t}{\left(2m' - 2m + \frac{1}{rC}\right)D + m\left(m - 2m' - \frac{1}{rC}\right)}$$

where m' is the damping exponent of the LRC circuit in the anode circuit of the valve.*

Now to a steady continuous-wave signal the impedance of the stopper circuit is ω^2L^2/R, and the amplification of such a signal is $\frac{\omega^2L^2}{R(r + \omega^2L^2/R)}\mu$. Hence in order that the valve shall amplify satisfactorily it is probable that $\omega^2L^2/(Rr)$ will lie between, say, 1 and 5. To simplify the analysis we must take some value for $\omega^2L^2/(rR)$. We shall suppose first of all that it is 5, so that the valve will be giving an amplification of $0{\cdot}83\mu$.

Then $$\frac{\omega^2 L}{r} = \frac{5R}{L}$$

$$\frac{1}{rC} = \frac{5R}{L} = 10m'$$

* m' does not include the damping added by the anode conductance of the valve, but is the damping exponent of the LRC circuit by itself.

Hence it follows that

$$i = K'\frac{\epsilon^{-mt}\sin\omega t}{m\left\{(12x-2)D + m(1-12x)\right\}} \text{ where } m' = xm$$

$$= K'\frac{\epsilon^{-mt}\left\{(12x-2)D - m(1-12x)\right\}\sin\omega t}{m\left\{-(12x-2)^2\omega^2 - m^2(1-12x)^2\right\}}$$

$$\doteqdot -K'\frac{\epsilon^{-mt}\left\{2\omega(6x-1)\cos\omega t - m(1-12x)\sin\omega t\right\}}{4m\omega^2(36x^2-12x+1)}$$

$$\doteqdot -\frac{\mu A p\epsilon^{-mt}\cos\omega t}{2rm(6x-1)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

$$\therefore L\frac{di}{dt} \doteqdot \frac{\mu A p\omega L\epsilon^{-mt}\sin\omega t}{2mr(6x-1)}$$

$$= \frac{\mu A p 5m'\epsilon^{-mt}\sin\omega t}{\omega m(6x-1)}, \text{ since } \frac{\omega L}{r} = \frac{10m'}{\omega}$$

$$= \frac{5x\mu A p\epsilon^{-mt}\sin\omega t}{(6x-1)\omega} \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Hence it is seen that the amplifier amplifies the P.D. applied to it in the ratio $\frac{5x\mu}{(6x-1)}$.

Should x have the value 1/6 this factor appears to be infinite; but this is not so, because in the analysis m has been neglected in comparison with ω, and also the applied P.D. has been assumed to be $\epsilon^{-mt}\sin\omega t$, when actually it is $\epsilon^{-mt}\,t\,\sin\sqrt{(\omega^2-m^2)}t$.

The condition when x equals 1/6 corresponds to the case when the decrement of the aerial is the same as the decrement of the stopper circuit together with the valve resistance in parallel. If this case is worked out without approximations, the complete expression for the current is

$$I \doteqdot -\frac{\mu A p}{2r}\epsilon^{-mt}\left\{t\cos\omega t - \frac{1}{\omega}\sin\omega t\right\}$$

The P.D. across the stopper circuit is therefore given by

$$L\frac{di}{dt} = \frac{\mu A p\omega L}{2r}t\epsilon^{-mt}\sin\omega t \doteqdot \frac{\mu A p m}{\omega}t\epsilon^{-mt}\sin\omega t$$

This expression represents a sine curve the maxima of which gradually grow to a maximum and then gradually die away to zero. The greatest maximum occurs at time $t = 1/m$ approximately, and this maximum is approximately equal to $0 \cdot 4\ (\mu A p/\omega)\sin\omega t$.

It is interesting to consider the values of the amplifications that obtain for various values of x.

If x is much greater than unity, $\frac{5x}{6x-1}$ approaches 5/6.

If x is equal to unity, $\frac{5x}{6x-1}$ is unity.

If x is equal to 1/6 the amplification may be considered to be $0 \cdot 4$.

If x is equal to 1/10, $\frac{5x}{6x-1}$ is equal to $1 \cdot 25$.

If x is equal to 1/20, $\frac{5x}{6x-1}$ is equal to $0 \cdot 3$.

But in addition to the component of current already considered there is the component due to the free oscillation of the stopper circuit. It is readily shown that the approximate expression for this is given by

$$L \doteqdot \frac{p\mu A}{2mr(6x-1)}\epsilon^{-6m't}\cos\omega t$$

and the complete expression for the P.D. applied to the next valve is

$$L\frac{di}{dt} \doteqdot \frac{5\mu x}{6x-1} \times \frac{Ap}{\omega}(\epsilon^{-mt} - \epsilon^{-6m't})\sin\omega t$$

It can be seen from this expression that if m' is much less than m, then the free oscillation is much the most persistent and consequently the most important in causing disturbances. Hence, although great reduction of the decrement may reduce the amplitude some 50 per cent. it is at the expense of increased persistence.

The critical adjustment which makes the resultant amplifier decrement equal to that of the aerial is no doubt to some extent advantageous, but it is difficult in practice to attain. The safest plan appears to be to keep the stopper circuit decrement much greater than that of the aerial. It would appear that the best procedure in practice is to reduce the stopper circuit decrement until further reduction increases the signal very little; when this has been done the aerial decrement should be reduced to the limit imposed by stability or speed of signalling. Probably the most satisfactory method is to build the stopper circuit so that its inherent decrement is low enough to get the required degrees of amplification without resorting to retroaction, and to apply retroaction in the aerial circuit and there only.

9. Effect of Slightly Distuning the Aerial.

It is often considered that atmospheric disturbances are somewhat reduced if the aerial is slightly distuned from the signal. Since the frequency of the atmospheric and the signal are widely separated, a slight alteration of the aerial tuning cannot sensibly alter the magnitude of the high-frequency current set up by the atmospheric; but it will make the frequency of this current appreciably different from that of the signal to which the stopper circuit is tuned.

Consequently the amplifier, which is supposed to be highly selective, will not function as efficiently at the frequency of the current set up by the atmospheric as it does at the signal frequency. Distuning the aerial, however, has not only the desired effect of throwing the atmospheric out of tune with the amplifier but it has also the undesired effect of weakening the signal. In order to benefit by the method it is evidently necessary to choose the decrements of the circuits in such a way that the advantage gained by reducing the atmospheric is not more than counterbalanced by the weakened signal; in fact the system is admissible only when the aerial has a relatively high decrement.

The P.D. produced by the atmospheric between the terminals of the aerial tuning inductance is given (see Section 5) by

$$L\frac{di}{dt} = A\frac{p}{\omega}\epsilon^{-mt}\sin\omega' t$$

where ω' is 2π times the frequency of the slightly distuned aerial. The initial amplitude of this P.D. is sensibly independent of the extent of distuning and of aerial decrement. We may then consider that the atmospheric P.D. applied to the amplifier is independent of circuit conditions, while the signal P.D. depends greatly on decrement and the amount of distuning.

The P.D. produced by the signal $e = E \sin \omega t$ is given by

$$L\frac{di}{dt} = \frac{E \sin \omega t}{\sqrt{\left[\frac{\delta^2}{\pi^2} + 4\left(\frac{\delta\omega}{\omega}\right)^2\right]}}$$

where $\delta\omega$ is the amount by which the aerial is distuned.

We shall consider an amplifier the circuits of which are arranged to give an output P.D. $\frac{4}{5}\mu$ times as great as the input P.D.; then the output voltage due to the signal will be given by

$$v = \tfrac{4}{5}\mu \frac{E \sin \omega t}{\sqrt{\left[\frac{\delta^2}{\pi^2} + 4\left(\frac{\delta\omega}{\omega}\right)^2\right]}} \quad . \quad . \quad . \quad (14)$$

Considering now the output voltage due to the atmospheric, we have, as previously,

$$\left\{D^2 + \left(\frac{R}{L} + \frac{1}{RC}\right)D + \omega^2\right\} i = \frac{\mu A}{rCL} \times \frac{p}{\omega} \epsilon^{-mt} \sin \omega' t$$

whence

$$i = \frac{10\mu A m'}{L} \cdot \frac{p}{\omega} \cdot \frac{\epsilon^{-mt} \sin \omega' t}{D^2 + D(12m' - 2m) + \omega^2 + m^2 - 12mm'}$$

$$\doteq \frac{10\mu A\omega\delta'}{4\pi L} \cdot \frac{p}{\omega} \cdot \frac{\epsilon^{-mt} \sin \omega' t}{\left(\frac{\delta\omega}{\omega}\right)^2 + \frac{1}{2\pi\omega}(6\delta' - \delta)D}$$

$$= -\frac{10\mu A}{L} \cdot \frac{\delta'}{4\pi\omega} \cdot \frac{p}{\omega} \cdot \frac{\epsilon^{-mt} \sin (\omega' t + \lambda)}{\sqrt{\left[\left(\frac{\delta\omega}{\omega}\right)^2 + \left(\frac{6\delta' - \delta}{2\pi}\right)^2\right]}}$$

$$L\frac{di}{dt} = \frac{10\mu A\delta'}{4\pi} \cdot \frac{p}{\omega} \cdot \frac{\epsilon^{-mt} \sin (\omega' t + \lambda)}{\sqrt{\left[\left(\frac{\delta\omega}{\omega}\right)^2 + \left(\frac{6\delta' - \delta}{2\pi}\right)^2\right]}}$$

$$\equiv 0 \cdot 8K\mu\delta' \frac{\epsilon^{-mt} \sin (\omega' t + \lambda)}{\sqrt{\left[\left(\frac{\delta\omega}{\omega}\right)^2 + \left(\frac{6\delta' - \delta}{2\pi}\right)^2\right]}} \quad . \quad . \quad (15)$$

To compare the signal with the atmospheric it is best to give numerical values to the decrements δ and δ'.

The values of the expressions (14) and (15) have been worked out for various amounts of distuning up to 5 per cent in the two cases where $\delta = 0 \cdot 1$ and $\delta' = 0 \cdot 01$ and when $\delta = 0 \cdot 01$ and $\delta' = 0 \cdot 01$ respectively. The results are collected in Tables 3 and 4.

Figs. 8 and 9 exhibit two curves plotted from the results of these tables and show the relation between the ratio of signal to atmospheric for various amounts of distuning.

It is clear that the distuning system is a very distinct advantage in the case when the aerial decrement is somewhat high, but is very disadvantageous when the aerial decrement is reduced by retroaction to a low value. It can be seen that the distuning method cannot give as good results as if the two circuits are kept dead in tune and the aerial decrement reduced to the lowest possible limit.

It must not be overlooked that the free oscillation has not been considered in the results of Tables 3 and 4.

TABLE 3.

$\delta = 0 \cdot 1, \quad \delta' = 0 \cdot 01.$

Amount of distuning	0·00	0·01	0·02	0·03	0·04	0·05
Amplified signal	$26\mu E$	$22\mu E$	$19 \cdot 5\mu E$	$17 \cdot 5\mu E$	$16 \cdot 3\mu E$	$15 \cdot 4\mu E$
Amplified atmospheric	$1 \cdot 3\mu K$	$0 \cdot 67\mu K$	$0 \cdot 51\mu K$	$0 \cdot 43\mu K$	$0 \cdot 38\mu K$	$0 \cdot 37\mu K$
Signal atmospheric	$20\frac{E}{K}$	$33\frac{E}{K}$	$38\frac{E}{K}$	$40\frac{E}{K}$	$43\frac{E}{K}$	$45\frac{E}{K}$

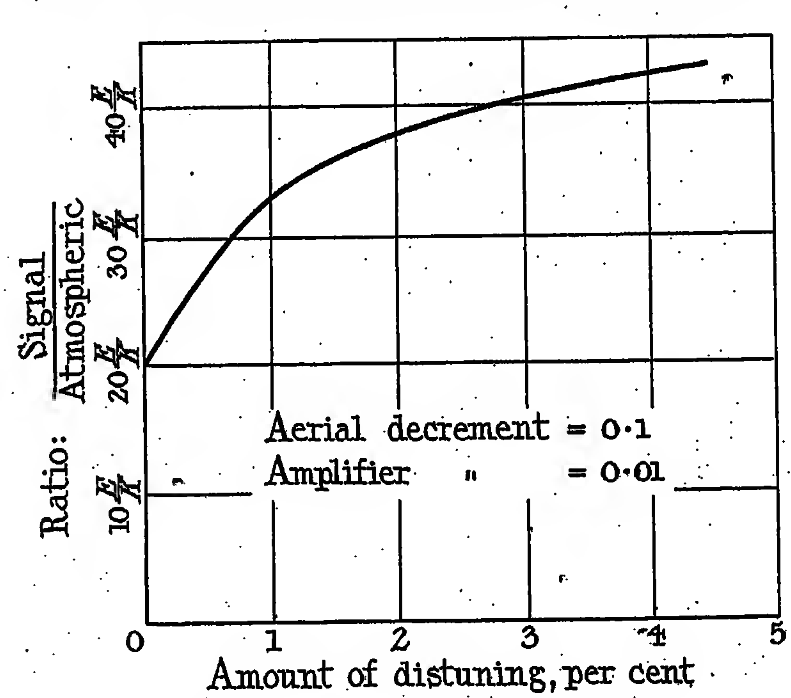

FIG. 8.—Effect of distuning aerial.

Aerial decrement = 0·1.
Amplifier decrement = 0·01.

This free oscillation is in tune with the next amplifier of the chain, and consequently it is important that its amplitude should be kept small and its decrement high. Indefinite reduction of the amplifier decrement will

merely serve to increase the importance of this term and thereby make the net advantage of distuning consider-

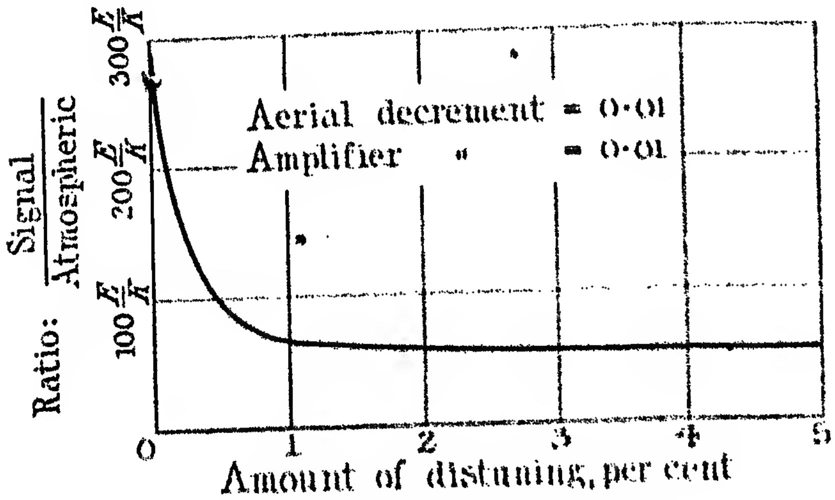

FIG. 9.—Effect of distuning aerial.
Aerial decrement = 0·01.
Amplifier decrement = 0·01.

ably less than would appear from calculations based on formulæ (14) and (15).

10. RATIO OF SIGNAL TO ATMOSPHERIC WITH APERIODIC ANTENNA AND SELECTIVE AMPLIFIER.

The correct design of antenna circuit for working with an aperiodic aerial has been considered in Section 6.

whence it follows that

$$i = -\frac{\mu A x}{r}\frac{p}{\omega}\left[\frac{\epsilon^{-\frac{\omega}{x}t}}{1+1/x^2} - \epsilon^{-bt}\left(\cos pt - \frac{b}{p}\sin pt\right)\right]$$

when t is equal to 0

$$\frac{di}{dt} = \frac{\mu A x}{r}\cdot\frac{p}{\omega}\left[\frac{\omega}{x(1+1/x^2)} - 2b\right]$$

The complete solution is given by

$$i = B\epsilon^{-Mt}\sin\omega t + C'\epsilon^{-Mt}\cos\omega t$$
$$-\frac{\mu A x}{r}\cdot\frac{p}{\omega}\left[\frac{\epsilon^{-\frac{\omega}{x}t}}{1+1/x^2} - \epsilon^{-bt}\left(\cos pt - \frac{b}{p}\sin pt\right)\right]$$

When $t = 0$, $i = 0$ and $\frac{di}{dt} = 0$

$$\therefore C' = \frac{\mu A x}{r}\times\frac{p}{\omega}\left[\frac{1}{1+1/x^2} - 1\right]$$

and $$\omega B = -\frac{\mu A x}{r}\times\frac{p}{\omega}\left[\frac{\omega}{x(1+1/x^2)} - 2b\right]$$

Suppose $x = 1$

then $$C' = \frac{\mu A}{r}\times\frac{p}{\omega}\times\frac{1}{2}$$

and $$B = -\frac{\mu A}{r}\times\frac{p}{\omega}\times\frac{1}{2}$$

TABLE 4.

$\delta = 0·01, \quad \delta' = 0·01.$

Amount of distuning	0·00	0·01	0·02	0·03	0·04	0·05
Amplified signal	$260\mu E$	$42\mu E$	$29\mu E$	$24\mu E$	$21\mu E$	$19\mu E$
Amplified atmospheric ..	$0·9\mu K$	$0·61\mu K$	$0·48\mu K$	$0·41\mu K$	$0·37\mu K$	$0·31\mu K$
Signal atmospheric	$290\frac{E}{K}$	$69\frac{E}{K}$	$60\frac{E}{K}$	$59\frac{E}{K}$	$58\frac{E}{K}$	$57\frac{E}{K}$

We are now in a position to consider how the combination of an aperiodic aerial and selective amplifier compares with the combination of tuned aerial and selective amplifier. If the signal E.M.F. in the aperiodic aerial is $e = E\sin\omega t$, then the P.D. across the resistance inserted in the aerial is also sensibly equal to $v = E\sin\omega t$, and hence the output voltage from the amplifier will be sensibly equal to $v = \frac{1}{2}\mu E\sin\omega t$.

The input P.D. due to the atmospheric is given [see Section 6, formula (5)] by

$$v = -xA\frac{p}{\omega}\left\{\epsilon^{-\frac{\omega}{x}t} - \epsilon^{-bt}\left(\cos pt - \frac{b}{p}\sin pt\right)\right\}$$

Hence the differential equation representing the current through the stopper circuit inductance is

$$\left\{D^2 + \left(\frac{R}{L} + \frac{1}{rC}\right)D + \omega^2\right\}i$$
$$= \frac{\mu A p\omega x}{r}\left\{\epsilon^{-\frac{\omega}{x}t} - \epsilon^{-bt}\left(\cos pt - \frac{b}{p}\sin pt\right)\right\}$$

If now $x > 5$, say

$$C' \doteq 0$$
$$B \doteq -\frac{\mu A}{r}\times\frac{p}{\omega}$$

Hence if $x = 1$, the resulting high-frequency current is

$$i = 0·7\frac{\mu A}{r}\times\frac{p}{\omega}\epsilon^{-Mt}\sin(\omega t + \lambda)$$

and if $x > 5$

$$i \doteq \frac{\mu A}{r}\times\frac{p}{\omega}\epsilon^{-Mt}\sin\omega t$$

Hence the value of $1/(CR)$ makes very little difference to the magnitude of the high-frequency disturbance set up. It was pointed out in Section 6 that, if the atmospheric was truly of the form assumed, then the initial rate of rise of atmospheric P.D. applied to the amplifier is independent of $1/(RC)$ and equals Ap. Hence this is merely another example of the fact that if a low-

frequency P.D. is applied to a high-frequency circuit of low decrement, the resulting disturbance depends not on the amplitude of the low-frequency P.D. but on its initial rate of increase.

The output P.D. from the amplifier is given by

$$L\frac{di}{dt} \doteqdot \frac{\mu A p L}{r}\epsilon^{-Mt}\cos\omega t$$

and if $$\frac{L}{r} \doteqdot \frac{5R}{\omega^2 L} = \frac{5}{\pi}\cdot\frac{\delta'}{\omega}$$

then $$L\frac{di}{dt} \doteqdot \frac{5\mu A p \delta'}{\pi\omega}\epsilon^{-Mt}\cos\omega t$$

and the ratio $$\frac{\text{Signal}}{\text{Atmospheric}} = \frac{E\pi\omega}{A6p\delta'} \quad . \quad . \quad . \quad (16)$$

The corresponding ratio for a tuned aerial is [see Section 5, formula (3)]

$$\frac{\text{Signal}}{\text{Atmospheric}} = \frac{E\omega\pi}{Ap\delta}$$

Expressions (3) and (16) are seen to be very similar in form, and it is possible to make them numerically equal. Since δ' represents the decrement of the stopper circuit alone without the decrement produced by the valve inductance, δ' can be very much smaller than δ. With the amplifier adjustment considered when $\delta = 6\delta'$ the tuned aerial circuit and the whole amplifier circuit would have the same decrement, and in that case also $M = m$ so that the tuned aerial and aperiodic aerial would be identical.

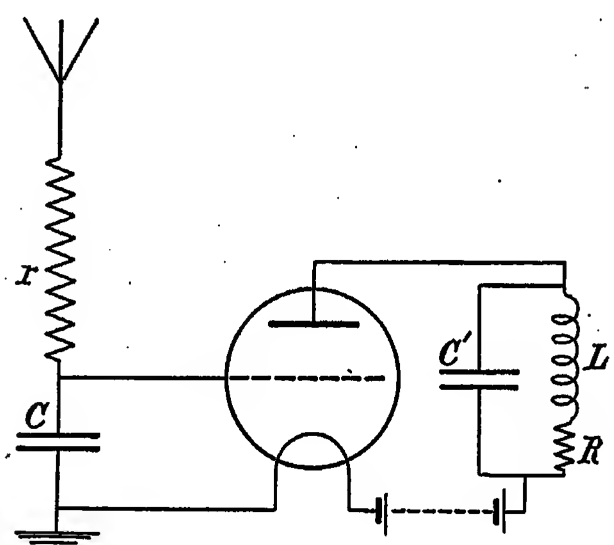

FIG. 10.

Hence if an aperiodic antenna is required for multiplex reception it may be used without fear of increasing the atmospheric disturbance.

Instead of using an aperiodic antenna in the way just described, we may place a condenser in series with it and apply the P.D. across this condenser to a selective amplifier (see Fig. 10). This method appears to be advantageous because the initial rate of change of the P.D. applied to the amplifier is zero for all forms of atmospheric; but since the signal P.D. applied to the amplifier is now only a small fraction of the signal E.M.F., the signal is reduced as much as the atmospheric and a net gain does not result. If K is the capacity and r the resistance of the antenna, and C the capacity of the series condenser, it may be shown that an atmospheric $e = A \sin pt$ will produce a potential difference V across the condenser C which is given by

$$V = \frac{pAr}{C(p^2r^2+\gamma^2)}\left\{-\cos pt + \frac{\gamma}{rp}\sin pt + \epsilon^{-\frac{\gamma}{r}t}\right\}$$

where $\gamma \equiv \dfrac{K+C}{KC}$.

It can be shown that V will produce a high-frequency P.D. across the stopper circuit inductance L which is given by

$$V' \doteqdot \frac{Ap}{\omega}\cdot\frac{Lg}{Cr}\epsilon^{-mt}\cos\omega t \quad \text{if} \quad \frac{\gamma}{r} << \omega$$

where g is the anode-grid conductance of the valve and m is the damping exponent of the stopper circuit together with the valve. The signal potential difference V_s is given by

$$V_s \doteqdot -\frac{E\cos\omega t}{r\omega C}\times\frac{y}{y+1}\mu$$

where $\dfrac{y}{y+1}\mu$ is the amplification factor of the valve.

It follows that the ratio

$$\frac{\text{Signal}}{\text{Atmospheric}} = \frac{E\omega\pi}{Ap\delta}\times\frac{y}{y+1} \quad . \quad . \quad (17)$$

where δ is the decrement of the stopper circuit by itself. If, as in Sections 10 and 8, we give y the value 5, formula (17) becomes identical with formula (16). If $\gamma/r \doteqdot \omega$ it may be shown that the ratio is still given by formula (17). Hence it appears that a tuned aerial or the combination of any form of aperiodic antenna with a selective amplifier can always be made to give an identical ratio of signal to atmospheric by simply adjusting the decrement of the first oscillatory circuit of the chain. It is possible that with a given selective amplifier the ratio of signal to atmospheric can be improved by replacing the tuned aerial by an aperiodic one, but it cannot be improved beyond the point which could have been attained if the decrement of the tuned antenna had been reduced to the lowest possible limit.

11. Practical Limitations of Decrement.

In the previous portion of this paper it was tacitly assumed that signals and atmospherics did not occur simultaneously, and that a signal lasted long enough to allow the current in the oscillatory circuit to build up to its final value; but if these conditions obtained in practice, stability would be the only limitation imposed on the decrement of circuits. For signals which last for a time T only, it may be shown that formula (3) becomes

$$\frac{\text{Signal}}{\text{Atmospheric}} \equiv \frac{E\omega\pi(1-\epsilon^{-n\delta T})}{Ap\delta} \equiv Z\frac{(1-\epsilon^{-n\delta T})}{\delta}$$

For a given wave-length and speed of signalling n and T are fixed. Let their product be denoted by K. For a

given value of K, Table 5 illustrates how the ratio depends on $n\delta T$.

TABLE 5.

$n\delta T$	Ratio : $\frac{\text{Signal}}{\text{Atmospheric}}$
2	$0 \cdot 43KZ$
1	$0 \cdot 63KZ$
1/2	$0 \cdot 8KZ$
0	$1 \cdot 0KZ$

Table 5 shows that there is little to be gained by reducing δ below the point at which $n\delta T = \frac{1}{2}$, but it is probable that considerations of shaping make it impossible to reduce $n\delta T$ much below 2.* But even with low-speed signalling we cannot reduce the decrement indefinitely without blurring the signals and making them unreadable. Some experiments have been made by Mr. F. P. Best at the Engineering Laboratory, Cambridge, who finds that $n\delta$ cannot be reduced much below 100 without causing troublesome ringing. If we make $n\delta$ equal to 100, formula (3) becomes

$$\frac{\text{Signal}}{\text{Atmospheric}} \equiv \frac{E\omega^2 1}{Ap \times 200} \doteq \frac{E}{A} \times 10^5 \text{ if } \frac{\omega}{p} = 100 \text{ and } \lambda = 6\,000m$$

$$\text{or } \doteq \frac{E}{A} \times 10^7 \text{ if } \frac{\omega}{p} = 1\,000 \text{ and } \lambda = 600m$$

This ratio should be compared with that given at the end of Section 5.

12. Effect of the Atmospheric on the Rectifier and the Low-Frequency Amplifiers.

Having traced the course of the atmospheric through the successive stages of the aerial and the high-frequency amplifiers, we must now consider its effect on the rectifier and low-frequency amplifiers.

The P.D. applied to the rectifier consists of a small low-frequency component and a relatively large high-frequency component. It follows from formula (11) that the low-frequency output P.D. from the first amplifier is about $\frac{5\mu}{\pi}\delta' \frac{p^3}{\omega^3}A$, and from the second amplifier is approximately $\frac{25\mu^2}{\pi^2}\delta'\delta'' \frac{p^4}{\omega^4}$. If p/ω is of the order of 1/100, this P.D. will be about one hundred-millionth of the atmospheric E.M.F., or less than a microvolt in value. But the high-frequency P.D. applied to the rectifier will be (with two high-frequency amplifiers) $\mu^2 \frac{p}{\omega}$ of the atmospheric E.M.F., and will be of the order of a volt or two. Hence, although the rectifier, together with its low-frequency transformer, forms an amplifier suitable for the low-frequency portion of the atmospheric, the P.D. handed on to the first low-frequency transformer by this means will be negligible in comparison with that due to the rectified current produced by the high-frequency portion. The low-frequency component may now be finally dismissed from consideration.

Although we can increase the ratio of the signal P.D. to the initial P.D. of the atmospheric by decreasing the decrement of the circuit, we thereby increase the persistence of the atmospheric. Before finally recommending low decrements we must estimate the quantity of electricity that the atmospheric will cause to flow through the rectifier. A powerful heterodyne generator makes the quantity rectified per cycle of applied P.D. sensibly proportional to the area of the positive half-cycle of applied P.D. Let it be K times this area, where K is a constant depending on the rectifier.* If the applied P.D. is of the form $e = B\epsilon^{-n\delta t} \sin \omega t$, it can readily be shown that, if δ is small, the total area of all the positive half-waves is $2B/(\omega\delta)$. Hence the quantity Q_A rectified by the atmospheric $e = A\frac{p}{\omega}\epsilon^{-mt} \sin \omega t$ is given by

$$Q_A = \frac{Ap}{\omega} \times \frac{2K}{\omega\delta}$$

Let the duration of a Morse dot be T seconds. We shall suppose that the signal P.D. reaches its full value in a time that is appreciably less than T. Then the quantity Q_S rectified by the signal $v = \frac{E\pi}{\delta} \cos \omega t$ will consist of a quantity $\frac{E\pi}{\delta} \times \frac{2KTn}{\omega}$ produced during the transmitted dot, and a quantity $\frac{E\pi}{\delta} \times \frac{2K}{\omega\delta}$ produced after the transmitter key has been raised.

$$\text{Hence } Q_S/Q_A = \frac{E}{A} \times \frac{\pi}{\delta} \times \frac{\omega}{p} \times \frac{\left(\frac{Tn}{\omega} + \frac{1}{\omega\delta}\right)}{1/(\omega\delta)}$$

$$= \frac{E}{A} \times \frac{\pi}{\delta} \times \frac{\omega}{p} \times (1 + n\delta T) \quad . \quad . \quad (18)$$

If T is long enough for the signal to reach its full P.D., then formula (18) shows that the final ratio of signal to atmospheric is always greater than the ratio given by formula (3). If audible reception requires that $n\delta$ shall not be less than 100, then $n\delta T$ must not be less than 4 for 30 words per minute, or 8 for 15 words per minute. Imposing that limitation on equation (18) we have

$$\frac{Q_S}{Q_A} \doteq \frac{E\pi\omega}{A\delta p} \times 6$$

$$= \frac{E\omega^2}{Ap} \times \frac{1}{30} \text{ if } n\delta \doteq 100$$

If we allow for the gradual rise of signal P.D. it may be shown that in the limiting case when δ is zero

$$\frac{Q_S}{Q_A} = \frac{E\omega^2}{Ap} \times \frac{T}{2}$$

The rectifier will impose a limiting action on very strong atmospherics if its anode potential is chosen suitably with respect to the strength of the heterodyne.

* See paper by L. B. Turner: "The Relation between Damping and Speed in Wireless Reception," *Journal I.E.E.*, 1924, vol. 62, p. 192.

* E. B. Moullin and L. B. Turner: "Thermionic Triode as Rectifier," *Journal I.E.E.*, 1922, vol. 60, pp. 711 and 717.

Also, if we make the second acoustic amplifier selective to the beat note between signal and heterodyne, and make the natural frequency of the first amplifier very different from that beat note, we can obtain some degree of discrimination between signals and atmospherics.

13. Conclusion.

Common experience has shown that the difficulty of combating atmospherics is greater than the mathematical analysis contained in this paper would suggest, for to cause great disturbance it seems that atmospherics would have to be at least 10 times as strong as those measured by Watt and Appleton. There are at least two reasons why the analysis makes the problem easier to solve than it is. First, the atmospherics delineated by Watt and Appleton are necessarily single discharges which produce a click in the receiver, but it often happens that a series of discharges occur in rapid succession and will cause much more disturbance than a single click. Also, Watt and Appleton observe that high-frequency ripples are often superposed on the main atmospheric and it is possible that they are the main cause of disturbance. Thus a superposed ripple having one-tenth the amplitude and 10 times the frequency of the main atmospheric will at least double the disturbance caused by the discharge. Hence, although it cannot be hoped that the analysis represents the whole problem, it is probably a close approximation to it. The analysis shows that the direct effect of the low-frequency component of current is always negligible, and that the disturbance is caused by the high-frequency oscillation produced by the atmospheric. It also shows that an aperiodic antenna cannot in itself be any protection against atmospherics, and that a tuned loop aerial is more selective than a tuned antenna. For a given wave-length it appears that the disturbance does not depend in any way on the ratio of inductance to capacity, but only on the decrement of the first oscillatory circuit. It is shown that for audible reception the decrement of the first oscillatory circuit should be reduced until the phenomenon of "ringing" becomes troublesome; the receiver is then in the best condition to battle with atmospherics, and further protection can be obtained only by use of special apparatus such as current limiters or directional devices.

Discussion before the Wireless Section, 6 February, 1924.

Dr. E. V. Appleton: It was natural that we should make calculations similar to those described by the author as soon as we had seen the wave-forms on the oscillographic screen. In work of this type I used the well-known mathematical expressions for pulses $E = Ate^{-\lambda t}$ and $E = A(e^{-\lambda t} - e^{-2\lambda t})$. The net results were similar to those of the author in that they showed that the effect of an atmospheric pulse increases with increase of amplitude and also with decrease of duration, but no attempt was made to discuss the effect on various circuits in the comprehensive way the author has done. At first I thought that the author's work was a little premature in that it was based on a preliminary report of our experiments. In that report we were mainly concerned with trying to prove that it was possible to devise an apparatus which would show atmospheric wave-forms, and the analysis of the 600 wave-forms in that report is not to be considered final. During the year many improvements have been made in the experimental gear. Also something like 8 000 wave-forms have been observed, mainly by Mr. J. F. Herd, a full account of which will be published shortly. But it appears that wave-form, apart from ripples, is not of much importance in the analysis and so the author's work is independent of our later results. The interesting outcome of Mr. Best's experiments is that the relief we can get from atmospheric interference by feebly damped circuits is limited by "ringing," and it seems certain that the main solution at present lies in short-wave working and in directional reception. We therefore have to ask ourselves the question: Where do atmospherics come from in the first place? Much has been written in answer to this question and many theories have been proposed. To these theories I wish to add another, and that is, that atmospherics are caused by lightning flashes or discharges from thunder-clouds. It is, of course, well known that lightning flashes do cause atmospherics, but this theory differs from the older ones in that we are to regard discharges from thunder-clouds as the major source of atmospherics, instead of, as previously, a very minor source. Some years ago (see *Year-book of Wireless Telegraphy and Telephony*, 1921, p. 1114) I pointed out that Mr. C. T. R. Wilson's observations on the electric field of thunder-clouds might be used in deducing the order of magnitude of the electromagnetic disturbance arising from lightning flashes. From these measurements we may deduce that a lightning flash is an aerial with an effective height only to be measured in kilometres and with a rapidly changing current of the order of 20 000 amperes. There seems no doubt that thunder-cloud discharges can be of sufficient magnitude to account for the radiation fields observed. It has often been argued that it is difficult to imagine sufficient lightning flashes on the earth's surface to account for the number of atmospherics observed, but I do not think that this is the case, as the following considerations show. It is known that the earth as a whole remains negatively charged in spite of the positive atmospheric current flowing into it, which is of sufficient magnitude to neutralize the charge in 10 minutes. The chief problem of atmospheric electricity is to determine how this negative charge is maintained. Mr. Wilson's theory is that the negative charge is replenished by the electricity from thunder-clouds either in the form of lightning flashes or intense ionization currents. According to one version of this theory we must regard the thunderstorm regions of the earth's surface as sending positive charges to the Heaviside layer and negative to the ground, either in the form of lightning flashes or ionization currents, and thus maintaining the Heaviside layer at a million volts positive with respect to the earth. In accounting for the maintenance of the earth's charge in this way it may be estimated that at least 1 000 thunder-clouds

are in action at any one time. I have tried to link up this theory of the thunderstorm origin of atmospherics with the directional observations of Hoyt-Taylor, Round, Watson, Watt and Schindelhauer on atmospherics, and it appears possible to get satisfactory correlation if we assume that the thundery regions are situated mainly on a wide equatorial belt (and in particular South Africa and South America) which acts as a permanent source of atmospherics. If we accept the theory the next point is to consider what general rules it gives as to the average direction of arrival of atmospherics at any point on the earth's surface, and what form the diurnal variation will take. It is a well-known fact (and one which I have noted particularly in Cambridge during the past 5 years) that there is a correlation between local time and thunderstorm frequency. Thunderstorms occur most frequently during the afternoon, and thus at that time we may expect places having the same longitude as the point in question to act as sources of atmospherics. So far as this point is concerned, the source of atmospherics should follow the sun. Secondly, there is the question of the proximity of a particularly thundery district either on or off the equatorial belt (e.g. a land area as opposed to a sea area). This region will be a marked source of atmospherics when its local time is afternoon. And thirdly, we have to consider the question of the ease of transmission of electric waves through the atmosphere between the point of origin and the point of observation, and the diurnal variation of the transmission factor. In this connection we may further note the possibility of the atmosphere's being aelotropic due to the conductivity of ionized gas being greater in the direction of the earth's magnetic field than in the direction at right angles. According to Mr. Wilson's theory the earth should possess its maximum negative charge when the maximum number of thunderstorms are in action at any part of the day. Now Mauchly has shown that the charge on the earth reaches a maximum about 18 G.M.T., and if we examine Schindelhauer's results we find that the atmospheric disturbances coming from the south and southwest reach a maximum at about the same time. This points to the conclusion that South Africa and South America may be regarded as the centres of gravity of the earth's thunderstorm and atmospheric-producing regions. It has often been argued that atmospherics come from places where lightning is not seen, but I think that many discharges take place from the top of a thunder-cloud (10 to 15 km up) to the Heaviside layer, in which case lightning may not be seen through the dark thunder-cloud. The general streaming of electricity from the thundery regions near the equator to the remainder of the earth may have on the magnetic declination an effect which is perhaps not negligible. It seems quite certain that the high-frequency ripples mentioned in the recent paper by Mr. Watt and myself are one of the chief causes of trouble in dealing with atmospherics, and more will be said of this in our second paper. Such high-frequency ripples will show a diurnal variation as compared with the low-frequency form due to atmospheric absorption, and thus will be especially pronounced near the source and at night.

Major A. G. Lee: I should like to mention another way of looking at this problem. Lord Rayleigh many years ago showed that an aperiodic pulse could be resolved into a number of sustained sinusoidal components forming an infinite spectrum. As an atmospheric can be resolved into these sustained sinusoids, it follows that, so far as our wireless receiving circuits are concerned, it is impossible to eliminate those sinusoidal components of the atmospheric which lie within the frequency curve of the apparatus. One result of this way of looking at the problem is that it does not matter where the low decrement in a circuit is placed, so long as there is a low decrement. Present wireless practice rather points to having the low-decrement effect at the low-frequency end of the wireless system, largely because it is more easily attained there. General experience agrees with the author's conclusion in so far as the reduction of atmospherics depends upon the decrement, but it does not quite agree with the analysis in the paper in regard to the position of that decrement. On page 358, taking the figures of Watt and Appleton of 0·1 volt per metre, the author says: "It would appear that E may be reduced to a few microvolts per metre and yet be sufficiently strong to hold its own against the atmospheric ordinarily to be expected in this country." This led me to think that Watt and Appleton's value of 0·1 volt per metre (which was taken in the winter time) did not apply to the average summer atmospheric, as practical experience shows that E must be much more than a few microvolts per metre in order to hold its own against the ordinary atmospheric. In Section 7, which deals with the effects of atmospherics on a tuned loop aerial, the ratio of signal to atmospheric on the frame and on the vertical antenna is given as ω/p. This means that the frame is 100 times better than the vertical antenna at 6 000 metres wave-length. That is not in accordance with practical experience. My own experience indicates that a frame is only better than a vertical antenna as regards its directive effect. Friis, in the *Radio Review* a few years ago, came to the conclusion that a frame and a vertical antenna were equal in effect. He took a different form of atmospheric, but he showed—and I think that is probably the fault in this particular analysis—that with a frame antenna there is a short interval of time during which the atmospheric acts in one leg of the frame only. At a later stage the atmospheric acts in both legs, the net E.M.F. being due only to the phase difference between the equal E.M.F.'s in each leg. The author in his analysis has taken that later stage as the commencement of his atmospheric. Actually the atmospheric would cause a strong, uncompensated E.M.F. to act in the loop on one leg for a short period before it reached the other leg. That is possibly the cause of the departure from what we know to be practical experience in this ratio of loop to vertical antenna. The author quotes from Mr. Best's experiments. I believe that Mr. Best used retroaction to obtain the low figure of $n\delta = 100$ in his experiments. Below that point he was troubled with what is known as "ringing" on the circuit. I am not quite clear what effect retroaction has on such ringing: without retroaction I have got as low as 80 on the low-frequency portion of the circuit without any sign of ringing what-

ever. There is one limitation on the use of low decrements which has not been discussed so far. That is, it is possible to reduce the decrement to such a point that satisfactory signals are obtained, either aurally or by relay, in the absence of atmospherics. In the presence of atmospherics, however, the operator prefers a high decrement to a low decrement for *aural* reception. The explanation, I think, is that so long as the atmospheric is represented in the telephones by a noise, the signal, which is a musical note, can be distinguished through a noise which is considerably stronger than itself. When a very low decrement is employed, the circuit filters out the side components of the noise, leaving only the centre components which produce a more or less musical tone of the same pitch as the signal. It now becomes impossible to distinguish aurally the signal from the atmospheric.

Mr. J. F. Herd: I should like to comment on the fact that the wave-forms by which these conclusions have been reached were only in the way of a preliminary report from the Radio Research Board Station at Aldershot. The continuation of the work has revealed a greater variety of shapes of atmospherics than was apparent when the smaller numbers in the first report were dealt with. The author's analysis shows that the actual shape is not so important. A new form of time base, which we are now using, gives a linear movement of the cathode-ray spot, and enables us to say with accuracy the order in which the various voltages occur. Actually the greater voltage or steeper slope does not always occur first. A type of atmospheric that would seem to have a far more serious effect on wireless receivers than any mentioned in the paper is in the form of a quasi-periodic single cycle, the half cycles being of sensibly equal voltage and of a sharp structure. These constitute 5 per cent of about 6 000 wave-forms taken, and are characterized by a greater field strength than all the other types, that is to say, a mean of about 0·2 volt per metre, which is considerably greater than the mean field strength of other atmospherics, except when there is comparatively local lightning. Even in Aldershot it is frequently observed that the disturbance is in the form of a background of considerable numerical frequency but of small individual amplitude, with disturbances of much smaller numerical frequency but of greater amplitude superimposed. Even the steady disturbance of small amplitude is, of course, still very large compared with a signal, and where considerable interference is experienced it is due to a large extent to the much greater number. It is quite possible that many atmospherics of apparently simple wave-form may be accompanied by minute ripples, which, although small in comparison with the fundamental form, may be large compared with a signal. There is no doubt that the effect of such ripples would be very important.

Mr. C. E. Horton: The general conclusions of the author agree with the observations of most wireless engineers who have had experience of atmospherics. I have examined the most important anti-atmospheric devices that have been published, and I certainly agree with the author that "the difficulty of combating atmospherics is greater than the mathematical analysis contained in this paper would suggest." The reason is, of course, that the full nature of the problem is not expressed in the original equations. The results are therefore true in themselves, but they are not the whole truth. It might perhaps have been wise to direct attention more to the quantities of electricity involved than to the potential differences, because the interference produced by atmospherics is not simply a question of amplitudes; it depends very largely upon the rapidity with which the impulses follow each other. For this reason the total quantity of electricity set in motion per second by the disturbing forces seems to be a better measure of their damaging effect than the mean or the maximum amplitude of the free oscillation. For instance, it is possible by using suitable limiting valves to arrange that the atmospherics have an amplitude in the telephones not greater than that of the signal. In some experiments on this matter I have examined the nature of the current through the telephones by means of a cathode-ray oscillograph, and I have satisfied myself that this state of limitation was actually obtaining. It might be thought that with a 1 : 1 ratio of signal to atmospheric, a signal of good strength would always be readable. But this is not so; it all depends on how frequent the atmospherics are. At the southern end of the Red Sea there are times when even Nauen is not readable, although the limitation of atmospheric amplitude may at the same time be perfect. In common with Major Lee, I should like to ask the author to explain a little more fully the equations which appear to show that the signal atmospheric ratio for a loop is ω/p times that of an aerial of the same decrement. I take it that the advantage of loop reception is now doubted by no one. It is the one anti-atmospheric device that always works; but is it as much superior to the ordinary aerial as this formula seems to hint? It has been held that the signal atmospheric ratio for a loop is two or three times that for an ordinary aerial. I have sometimes felt that that estimate is a little optimistic, but a superiority of several hundred times is suggested here. The discrepancy is so great as to warrant some explantion. Possibly a direct examination by cathode rays of the form of the E.M.F. induced by an atmospheric in a loop would throw light on the matter.

Mr. J. E. Taylor: The author points out that one of the limitations in decreasing the antenna decrement in order to obviate or reduce the effect of atmospherics is the phenomenon of ringing. No doubt that is true, but is it not in effect a recommendation for the use of shorter waves for signalling? I was much interested in the view which Dr. Appleton expressed, viz. that all atmospherics are due to lightning flashes. His definition of a lightning flash is rather broad. In his view, apparently, all electric disturbances of whatever kind that may occur in the course of a thunderstorm are lightning flashes. It appears to me, however, that it is likely that the flash itself is only the full development of an electrical disturbance, and that full development only occurs very occasionally, the initial disturbances which do not mature into a flash proper being much more frequent. I am not inclined to agree with Dr. Appleton's view because, for one reason, a wireless antenna

probably only picks up a very small proportion of the total atmospherics existing. This will be realized if an isolated earthed telephone line is used instead of a wireless antenna for picking up atmospherics. They can then be frequently heard in great profusion and with their various sound characteristics faithfully reproduced, so that numerous different types can be picked out which repeat themselves at irregular intervals. Individual lightning flashes can also be readily recognized on such a circuit, though doubtless certain high-frequency atmospherics may be ignored by the simple telephone receiver. Some of the types heard are palpably not lightning flashes, whatever else they may be.

Mr. R. H. Barfield: To me the most interesting point in the paper is the great superiority which the author's analysis gives to the loop over the antenna from the point of view of freedom from atmospherics. If his view were correct, the use of the antenna for reception purposes would be likely to disappear. He admits, however, that there is no experimental confirmation of this conclusion. One possible explanation of this discrepancy between theory and the observed fact is that the loop in picking up the atmospherics may be acting as an antenna. That is to say, it may be the "antenna effect" of the loop which is responsible for the greater part of the atmospheric disturbances obtained in practice. When receiving signals on a loop the antenna effect may easily be of the order of 10 per cent of the loop effect, but for atmospherics the ratio of the former to the latter might conceivably be very much greater than 100 per cent, since the loop acting as an antenna would have a high decrement and this circumstance has been shown by the author to favour greatly the atmospheric as opposed to the signal. Even if the loop were compensated for antenna effect as regards signals, it is probable that this compensation would not hold good for atmospherics.

Mr. W. J. Brown: In the recent Westinghouse Metropolitan-Vickers tests on 100-m transatlantic transmissions, the ratios of signals to atmospherics were carefully estimated, using a frame aerial and an open vertical antenna, and it was found that very little improvement indeed resulted from using a frame aerial. In this case, the wave-length being 100 m, $\omega/p = 6\,000$, so that even if 10 per cent were allowed for antenna effect on the frame aerial, a ratio of 600 could still be expected. The fact that on these very short wave-lengths there is no real advantage in using a frame aerial, seems to bear out the idea that there must be something not accounted for in these formulæ.

Mr. C. F. Phillips: The author mentions that the only hope he has of combating atmospherics lies in the use of some type of frame. One type of antenna does seem to show a higher ratio of signal to static than any other form at present known. I refer to the Beveridge antenna—a long, low wire perhaps only a few feet off the ground, of at least half a wave-length and preferably several wave-lengths in dimension. The previous speaker referred to the transmissions on 100 m from the United States. I have not tried to receive them on a frame aerial, but I have done a good deal of reception on a high antenna normally subject to very considerable interference. On these short waves, the conclusions shown in Equation (3) seem to be very fully justified, as what most people take to be atmospherics I think are valve noises or noises that occur in the set. There is a very great disparity between the opinions of the author and those of Major Lee regarding the position in which retroaction might introduce negative resistance. I have always held the opinion that a more selective circuit can be obtained by introducing negative resistance as close to the aerial as possible, and personally I prefer that way of working. Reaction or retroaction, when applied to what the author has termed a "stopper" circuit, does not seem to be particularly valuable unless the decrement of the aerial circuit is quite low.

Major H. P. T. Lefroy: The author, in dealing with the reduction of atmospherics, appears to assume that their complete elimination is so improbable that this point does not need consideration. In this we should probably all be inclined to agree with him; the following remarks may, however, be of interest in this connection. At Cairo, in September 1917, I was experimenting on a four-wire aerial suspended from the top of the Great Pyramid to the Nile River level, i.e. a vertical height of about 600 ft. Atmospherics were, of course, extremely strong, and, as they hindered our work, I was constantly experimenting with a view to the reduction of their effect. On the occasion under consideration I was using a modified Marconi No. 16 tuner, arranged for combined high- and low-frequency magnification on a "Round" soft valve, with a carborundum detector, as usual, but instead of connecting the grid and filament direct to the aerial they were connected to a closed grid circuit which was not directly coupled to the aerial. The aerial was coupled magnetically to a tuned plate-circuit, and the latter was coupled also to the tuned grid circuit, so that the plate circuit acted as a filter to the grid circuit, and the arrangement was practically the same as that of a continuous-wave transmitter. I observed that when there was a certain intensity and direction of coupling between these three circuits, I could receive signals well with reduced filament current, and that the effect of atmospherics was then considerably reduced. On further reducing the filament current and then making these couplings tighter, and also slightly retuning the grid and plate circuits, I found that atmospherics became still weaker, and finally I completely eliminated them. I was adjusted to a wave-length of 600 m, and soon after obtaining this result I received exceptionally loud spark signals from Alexandria on this wave-length, thus proving that my apparatus was still very sensitive for the reception of desired signals. Unfortunately I had to leave Cairo for Baghdad two days later, and I can now find no detailed record of my circuits, nor have I since been able to reconstruct the exact arrangement necessary; perhaps some other experimenter may yet find this arrangement, or another one giving similar results.

Mr. J. Hollingworth (*communicated*): In a paper of this nature consisting chiefly of mathematical analysis the two points most suitable for discussion are the premises on which the fundamental formulæ are based, and the generalized conclusions drawn from the results. In the first of these categories falls the formula assumed for the shape of the atmospheric. Pending the develop-

ment of a photographic method of recording these traces, the scheme of hand reproduction of a visual trace seems to be hardly one on which a critical analysis can be based. In addition, the author refers to the importance of the ripples in the atmospheric wave-form in determining the initial rate of growth. I believe that the size of the spot in the oscillograph is comparable with its maximum amplitude, and it seems that under such conditions superimposed ripples of considerable amplitude might be present without being detected. I should like to ask the author how far the important statement—that the determining factor in the disturbance produced is determined by the initial rate of rise—holds for ripples whose frequency approaches that of the tuned circuits, and when it would require modification. Also, how far do the results of Section 5 hold for the ordinary case of a secondary circuit coupled to the aerial with the valve in the usual position; as the reduction of aerial resistance by retroaction appears to involve a considerable risk of throwing the whole aerial circuit into a condition of oscillation and consequently of interference? Two small points arise with regard to the very low decrements advocated by the author. One is that retroaction pushed to the limit cannot be regarded as a mere reduction of effective resistance only, but is also accompanied by modification of the other constants of the circuit; and the other that in a practical case the frequency of transmission is liable to swing considerably about its mean position. If the decrement be too low these swings will be accompanied by very large variations in signal intensity. The author is to be congratulated on grasping the fact, appreciated by far too few mathematicians, that, in a subject like this where conditions cannot be rigidly specified, the prime object is to indicate general conditions of behaviour rather than to give numerical results.

Dr. N. W. McLachlan (*communicated*): Equation (7) is in error, due to the assumption that di/dt is zero when t is zero. Taking the author's equation to the atmospheric, viz. $h = He^{-bt} \sin pt$, where h is the instantaneous value of the magnetic field, the value of $L \cdot di/dt$ is equal to $d(ANh)/dt = -pANH$ when $t = 0$, since there is then no ohmic voltage-drop in the circuit, the current being zero. In other words $L \cdot di/dt$ is equal to the voltage induced in the loop due to the variation in the magnetic field. Putting this value in the expression for i, and using the author's approximations, we find that $i \doteq (-p/\omega)\, ANHe^{-mt} \sin \omega t$. The ratio (maximum steady signal)/(maximum atmospheric) is then $(H'\pi\omega)/(H\delta p)$, which is similar to that for a tuned open aerial. It follows, therefore, that for the type of atmospheric under consideration, a tuned frame or loop has no advantage over a tuned open aerial, excepting that possessed in virtue of its directional properties. This only holds, of course, when the signal current in the loop has attained a sensibly steady value. With a circuit of very low decrement the initial and final transients would have to be taken into consideration. Apart from the analytical viewpoint, it is clear that Equation (7) does not truly represent the physical aspect of the matter, since the current in the loop cannot increase with increase in decrement of the atmospheric. Also from the equation immediately preceding (9) we can see that the presence of b in the denominator indicates something which is opposed to an accurate physical concept of the problem. In Section (12) it is shown that, except for the effect of the decay period at the termination of a Morse character, the ratio Q_S/Q_A is independent of the damping of the receiver circuit. The result of the analysis *expressed in this form* is apt to lead to the erroneous impression that no advantage is gained by using circuits of low decrement. Although the quantity of electricity rectified, due to either signal or atmospheric, increases with decrease in decrement, the vector sum or difference of the signal and atmospheric, prior to rectification, increases in favour of the signal. It is this resultant voltage with which we are concerned in reception. Moreover, it can be seen—on this voltage basis—that after rectification the lesser atmospherics become innocuous when the decrement is sufficiently low, for the voltage of the atmospheric—even when it is initially in opposite phase to the signal in the receiving circuit—is never large enough to cause any material alteration in signal

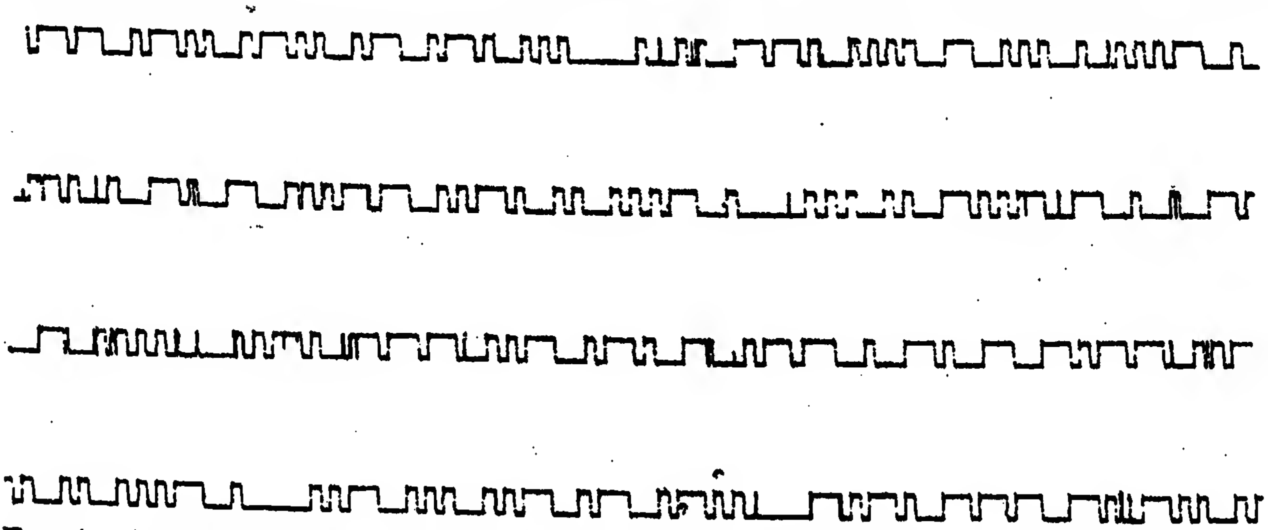

FIG. A.—Portion of message from New Brunswick, U.S.A. (WII), received at Chelmsford with a magnetic drum recorder on the 2nd July, 1923, using a frame aerial 3 ft. 9 in. square. Automatic transmission at 25 words per minute.

Atmospherics are clearly shown as thin upright strokes, which on the actual tape are quite straight. Owing to the rapidity of action of the instrument, the tape is not rendered illegible.

strength. So far as the recording of signals is concerned, the following remarks may be of interest. With strong atmospherics, provided they do not occur too frequently and the speed of transmission is not too high, it is possible, by using a suitable receiving circuit and a recording instrument which responds very quickly, to obtain a legible record. Fig. A shows a record of signals from New Brunswick (WII) taken at Chelmsford about 7 p.m. on the 2nd July, 1923, with my Magnetic Drum Recorder.* Despite atmospherics the tape is quite legible, since the duration of the impulses in the recorder circuit is much less than that of a dot. To secure this condition the circuit must be properly adjusted as regards damping; also as regards signal strength at the recorder. It should be observed that an oval, or chisel-pointed, siphon giving thin up and down strokes is essential to secure optimum legibility. When the record was obtained, the strength of the atmospherics was such that an open aerial accompanied by a receiving circuit comprising high-frequency retroaction and three low-frequency filter units of low decrement gave unreadable tape. For satisfactory recording, a frame 3 ft. 9 in. square having seven turns of stranded wire was used.† Stabilized retroaction was employed on the frame, and after suitable high-frequency amplification and heterodyning, the signals were rectified, working on the curvature of the anode-grid characteristic. The retroactive circuit was adjusted so that signals from the rectifier were clear-cut. Following the rectifier was a three-stage inter-valve tuned note filter (2 000 periods) with air-core coils of variable coupling, whose selectivity characteristic could be varied. The signals from the third valve were just "ringing," so that aural reception was not unpleasant. The voltage variation on the plate of the valve was applied to a d.c. converter unit of the type devised for the recorder.‡ The anode voltage on the note filters and converter unit was 240, so that substantial negative potentials could be applied to the grids of the amplifying valves to reduce the possibility of grid current or of the rectification or saturation limits being reached due to high-voltage atmospherics. There was no limiting valve device in the circuit, since sensibly linear amplification was desired.

Professor E. W. Marchant (*communicated*): The paper is open to the objection that must apply to all purely mathematical papers, namely, that the premises on which the mathematical analysis is based are incomplete. The paper by Messrs. Appleton and Watt recording the actual wave-shape of atmospherics has thrown a great deal of light on their true nature, but the records that they have published include only a relatively small number of atmospherics which have been observed at one time of the year only. An analysis such as that which has been made by the present author, although useful in throwing light on the factors which are of importance in reducing atmospheric disturbances, deals with only one or two forms of atmospherics, and one would like to see a more complete record of the actual wave-forms of atmospherics before coming to any conclusion as to the effectiveness or ineffectiveness of any particular method of reducing their effect. During the past year we have been making a number of experiments at Liverpool on methods of reducing disturbances due to atmospherics, and other causes, mostly on short wave-lengths. The disturbances which were found to be most troublesome were those due to electrical currents which produce effects not unlike the atmospherics recorded by Messrs. Appleton and Watt, and we have found experimentally that the use of an aperiodic aerial has considerably improved the signals received, i.e. it has reduced the ratio between the "atmospheric" and the signal. The reason for the improvement is, I think, that in the author's words, "the high-frequency part" of the solution of his differential equation has been cut down. On page 361 he refers to the method of slightly distuning the aerial from the received signal. As he says, such a distuning can have very little effect on the magnitude of the high-frequency current set up by the atmospheric, but will make the frequency of this current appreciably different from that of the signal for which the amplifier is tuned. The method, which was proposed many years ago by Marconi, of using two secondary circuits, both coupled to the antenna, one tuned and the other slightly distuned from the received signal, and balancing these circuits so that when they have equal currents flowing in them they will produce no effect on the receiver, is an illustration of the application of this method. In practice, however, it is stated by those who have used the method that the effect of slightly distuning one of the circuits is to alter very appreciably the currents due to atmospherics flowing round it, with the result that the two circuits no longer remain balanced for atmospheric disturbances, and considerable noise is produced in the receiver. I have suggested elsewhere that this effect may be due to the production by the atmospherics of oscillations in the aerial—what the author calls the "high-frequency current"—due to the complementary function in the solution of his differential equation. The use of the balanced system with an aperiodic aerial would, I believe, be much more beneficial and I hope it may be tried under conditions where atmospherics are very severe. On page 364 it is stated that the tuned aerial or the combination of any form of aperiodic antenna with a selective amplifier can always be made to give an identical ratio of signal to atmospheric by adjusting the decrement of the first oscillatory circuit of the chain. There is, of course, a fairly high "lower limit" to the decrement which can be obtained on an ordinary aerial for the reception of broadcast messages. For example, in order to reduce disturbance in buildings, it is often beneficial to use an "earth mat" instead of connecting to water pipes, although the effective resistance of the aerial circuit with this arrangement is increased and the signal strength diminished. The signal strength is, of course, cut down by the insertion of extra resistance in the aerial, and the signal is therefore correspondingly weakened, but the signal strength can usually be increased again as much as is necessary by using amplifiers. We have found in practice that the ratio of signal strength to noise due to disturbance or atmospherics can be appreciably increased by inserting

* *Journal I.E.E.*, 1923, vol. 61, p. 910.
† In this case the superiority of the frame, due to its directional properties, was clearly shown.
‡ *Loc. cit.*, Fig. 11.

resistance in the aerial. In his "Conclusion" the author points out what must be evident to everyone, viz. that the mathematical analysis contained in the paper does not correspond very closely to practical results. As he says, the mathematical analysis suggests that, to cause serious disturbance, atmospherics would have to be at least 10 times as strong as those measured by Watt and Appleton. The paper is of interest in showing the way in which the effect of certain types of atmospherics, such as have been recorded by Messrs. Watt and Appleton, can be reduced, but it will require a very much more elaborate analysis if the effect of the almost innumerable combination of disturbances that are met with in a wireless receiving set can be discussed mathematically. The only method which can lead to a practical solution of this problem is that of observation and experiment.

Mr. E. B. Moullin (*in reply*): Some speakers have suggested that a mathematical analysis is of little practical use since it does not include all the factors in the problem. I cannot agree with this. I think that finally the problem can be studied only experimentally, but unless the programme of such experiments is directed by analysis there cannot be, in my opinion, much hope of success. In this problem we have at least eight independent and controllable variables, as well as several independent variables not under control which arise from the atmospheric itself. Should an optimum combination of these many circuit variables exist, the chance of happening on it experimentally is very small. Had my analysis depended on an exact wave-form for the atmospheric it would indeed have been useless, but it shows that all atmospherics having the same initial rate of increase will produce sensibly the same result whatever their subsequent shape. I made this analysis preparatory to starting on experimental work, and I hope that it may be of use as a rough guide to other experimenters and show which are the most suitable avenues of attack.

Mr. Hollingworth asks if the analysis is valid for ripples of which the frequency approaches that of the tuned circuit. This question can be answered by means of the analysis in Section (4) leading up to formula (1). If the main atmospheric is accompanied by a slightly damped ripple of one-tenth its amplitude and having a frequency one-quarter that of the tuned circuit, the resulting current would be about 4 per cent greater than if it had been calculated from the true initial slope, but the presence of the ripple would increase the current about four times. Hence I think we may say that the disturbance is always sensibly proportional to the initial slope, but it is probable that the apparent initial slope as shown by the oscillograph as constructed at present may be quite different from the true value. As pointed out in Section (10), I think that this is the chief reason why the numerical part of this analysis appears to underestimate the difficulties of the problem. The analysis is valid for ripples, and to obtain correct numerical results we must doubtless take some other value for ω/p, say 6 or 7, and a reduced value for A, and add the result to the figures given in the paper. The results of Section (5) do not apply directly to the case of an intermediate tuned circuit between the antenna and the amplifier. This case is easily worked out because the low-frequency current can be ignored. The problem is therefore the same as that of spark reception with a double tuned circuit; and I think that the modifying factor to be applied to formula (3) would be negligible. With present conditions I agree that the unsteadiness of transmitter frequency is likely to impose a limit on the decrement, but I do not think that modification by retroaction of the circuit constants will affect the results, for the circuit will simply be retuned to suit those conditions.

Major Lee suggests that the atmospheric be represented by a Fourier integral. I did not do this because the analysis is more complex and less readily reduced to a generalized form. We must argue with care from the spectrum analysis of a pulse, because we must remember that the pulse is represented by the net effect of the simultaneous presence of every frequency. I do not think that we can necessarily ignore the presence of an infinite number of finite terms the frequency of which lies outside the resonance band. An aperiodic pulse can scarcely have the same effect as sustained and uninterrupted sinusoids having a frequency lying within an indefinitely narrow band. The sum of the infinite number of terms which lie outside that band must evidently produce a finite effect. Also the effect of those acoustic frequencies which lie within the band of the low-frequency amplifier, and which are vastly diminished by their passage through the high-frequency amplifiers [see Section (12)], may not produce the same effect as the high-frequency band which is amplified. Hence, although his argument for putting the low decrement anywhere in the chain may be correct, I do not think that it can be proved without detailed analysis.

Major Lee and Dr. McLachlan have both pointed out an error in the treatment of the loop aerial. I agree with Dr. McLachlan that I was in error in taking the initial value of di/dt to be zero, though if the loop be treated properly, in the way Major Lee suggests, the initial value of di/dt would be zero. I am grateful to those speakers for clearing up a point which common experience suggested was wrongly treated somewhere: their remarks answer the questions of several other speakers.

Mr. Horton suggests that the ratio which I have taken of signal to atmospheric does not represent the amount of disturbance produced, but since I have carried on my analysis to compare the quantities of electricity rectified [see formula (18)] I think that my ratio is a suitable measure of disturbance. If the effect of a succession of atmospherics is to be calculated it is necessary to consider the phase relation of one pulse to another.

If I understand Dr. McLachlan correctly, he suggests that an atmospheric which occurs during a Morse sign is not likely to produce as much disturbance as one which occurs during a space. If this be the case, my analysis, which does not consider the co-existence of signal and atmospheric, is more complete than I had supposed. The photographic records, however, do not seem to bear this out, for many atmospherics which occur during a sign bring the signal current down to zero. The signal current never seems to be increased by the atmospheric, but possibly this is due to a limit on the siphon.

DISCUSSION ON "LOUD-SPEAKERS FOR WIRELESS AND OTHER PURPOSES."

FURTHER COMMUNICATIONS TO THE DISCUSSION.*

Dr. W. A. Aikin (*communicated*): Without going too deeply into the science of phonology, which is a special branch of physiology for the study of the vocal organs and their functions, I think that some of its facts and principles might be useful in this discussion. We learn from the natural phenomenon known as the "resonator scale" that the resonation of vocal sound is two-fold. The upper, principally in the mouth, is a complex of high reinforcements with a definite resultant, giving vowel-character; whereas the lower, principally in the neck, expands for deeper reinforcements, giving "tone" or general quality to the sound. By this arrangement sonorous quality increases the amplitude of the sound waves by reinforcing deep harmonics, and the special characters of vowels may be represented by furrows of various designs upon the vibrations. Remembering that sound waves are in three dimensions, the delicacy of the sense which detects the shapes as well as the amplitude and frequency of the vibrations as they fall upon the drum of the ear, is wonderful indeed. In declamation we rely more upon deep resonation than upon force, and therefore the mechanical loud-speaker should be constructed with a view to preserving and even augmenting this function, if the natural "humanity" of speech is not to be impaired. I would therefore draw particular attention to the deeper effects of resonation in any experiments that are made; for the smaller vibrations of character will come through almost anything, whereas the deeper effects of tone are easily destroyed. Mentioning experiments reminds me that I sought for years in vain for a laboratory where acoustic experiments could be carried on. Then electricity and chemistry crowded out all else. Now, perhaps, someone will take up sound and make the best of mechanical voices on the same principles as the phonologist does of natural ones. Among the papers which I have written on the subject, I think that one read at the Society of Arts in 1906 and printed in their *Journal* would indicate to anyone the laws we follow. The subject of resonation is not yet fully investigated, and our greatest authority, Helmholtz, left behind him in his work on vowel sounds several unaccountable errors which have delayed our correct knowledge of the facts. His definition of the shape for the vowel AH, for instance, as "a funnel increasing with tolerable uniformity from the larynx to the lips," is anatomically impossible. Any loud-speaker made upon that pattern would, in my opinion, cut off much of the full quality or tone reinforced in the lower hollow and emitted through an open throat.

Mr. L. Miller (*communicated*): Prof. Rankine alludes to thermal receivers. Like many other useful inventions, these originated in this country and have been almost entirely dropped, while other nations have continued to develop them. Many patents have been taken out on the Continent and in America for heat-operated receivers, chiefly of the glow-lamp type, in which the air takes up the vibrations from a hot wire, no diaphragm being employed. Such receivers have been placed on the market, but it is obviously very difficult to compete with such a good and heavily-capitalized instrument as the ordinary electromagnetic telephone. I have had no experience with the thermal receivers in question, nor with the straight-wire kind with one end fixed to a diaphragm, but have made many experiments with the loose-contact receiving microphone type, which, in my opinion, is also actuated by expansion and contraction. I gave a demonstration with them in this hall, before the Wireless Society, in November 1921. They reproduce speech and music very clearly, but not at all loudly, as compared with the ordinary telephone. As claims have been made in the electrical Press (though not by me) that they can be used for loud-speaking purposes, I have recently tried at what distance from one of my receivers speech could be heard so as to be understood, and I found it to be about 3 ft. No horn was employed. One contact of fused marcasite was fixed in the centre of a large mica diaphragm, slightly pressed by another contact of hard synthetic galena. It seems very unlikely that the instrument has reached anything like finality in my hands alone, and I shall therefore conclude by endorsing the words of Prof. Fleming, in the last Kelvin Lecture,* that it is well worth further study.

Professor A. O. Rankine (*in reply*): The outstanding fact which emerges from this discussion is that apparently we cannot yet get sufficient loudness for loud-speaking purposes without relying to a considerable extent upon resonance. Perhaps in the future there will be developments on the practical side which will enable us to escape from this position, and I feel sure that this would lead to great improvement. For the present, however, we have to make the best of the actual situation, and this fact makes my opinion coincide with that of Mr. Nash, who has, I think, misinterpreted my remark about horns. I would advocate the elimination of these devices only if up to the point where their function begins the acoustic output has already suffered no distortion from resonance. If, on the contrary, as Captain Cohen has so clearly explained, present circumstances compel us to choose between pure quality and enough intensity, I agree with Mr. Nash as to the value of horns in that they may render resultant resonance less selective. They may, as I have already indicated in my introductory remarks, be used to provide additional resonances so as to balance other inevitable ones in other parts of the essential frequency scale. It would, however, be a rather fatal mistake to fashion them to suit any special vowel, as is half suggested at the end of Dr. Aikin's remarks.

* See page 265.

* *Journal I.E.E.*, 1923, vol. 61, p. 613.

Mr. Smith has suggested an arrangement suitable for visual observations on the quality of transmission. In this system the original sounds on the one hand, and the loud-speaker output on the other, are to be picked up respectively by two "as nearly as possible identical" telephone receivers, and the results recorded simultaneously on an oscillograph. I should prefer to impose the additional condition that the telephone receivers should be completely non-resonant; and I should not feel happy about the oscillograph itself unless it possessed the same negative attribute. It is a little surprising that Mr. Smith did not specify a cathode-ray oscillograph. Perhaps he recognizes no other! Mr. Sutherland in his introductory paper speaks of "desirable reverberation," more particularly in relation to music, but also as regards speech; but I still adhere to the opinion that reverberation is a thing which we have to put up with in order to hear loudly enough, and that we have virtually to learn several different languages, musical and otherwise, according to the conditions of listening. Does a speaker or a band, after all, sound so "dead" in the open air if we are close enough to hear? I disagree, however, rather reluctantly, for Mr. Sutherland's view seems to provide me with an excuse for inability to appreciate some modern music. If a correct amount of overlapping and blending by the agency of reverberation forms an essential part of the music, it might with some force be argued that I had not yet been fortunate enough to listen to the work of, let us say, Mr. Arnold Bax, in the right concert hall.

Mr. L. C. Pocock (*in reply*): Mr. Marris disagrees with the statement that a horn is the ideal form of coupling between the diaphragm and the air, and considers that one becomes tired of the horn resonance; further, he states that the presence of horn resonance can be proved by removing the horn. I should like to point out, however, that the use of a horn cannot be so lightly dismissed. It is easy to design a horn with strong resonance, and this is done in horn-type musical instruments; it is also possible, though less easy, to design a horn with much weaker resonance. The former is analogous to a resonance transformer or resonant transmission line, the latter to a transmission line in which the inductance and capacity vary continuously from end to end, and such an arrangement may, in principle, be a maximum energy coupling, although the application of the principle is restricted by the length of the horn. One may easily tire of the resonance of a bad horn, but a good horn has a far from evident fundamental, with many partials, and it can scarcely be claimed that the change of tone on removing a horn of this type proves anything, because the increased diaphragm resonance resulting from reduced damping introduces far more distortion than was caused by the horn.

Mr. Voigt endeavours to show that the efficiency of a loud-speaker is considerably greater than 1 per cent. In a reacting circuit of the kind which he describes, the oscillation point is conditioned by $\eta_1\eta_2\eta_3 = 1$, where η_1, η_2, are the loud-speaker efficiencies and η_3 is the amplifier power-efficiency. Mr. Voigt overlooks the fact that the power amplification is the square of the voltage amplification, so that if $\eta_1 = \eta_2$, and $\eta_3 = (25)^2$—using the lowest figure assumed—the loud-speaker efficiency at resonance is only 4 per cent, and the average efficiency a good deal lower. It is rather doubtful whether types of receivers having less-pronounced resonance peaks would sustain oscillations with so small an amount of amplification as that described. My own calculation of the efficiency as less than 1 per cent was based upon the estimate that normal speech represents an average emission of energy at the rate of 125 ergs per second (*Physical Review*, March 1922) and that the most efficient loud-speaker obtainable requires approximately 0·0005 watt to produce the same speech intensity. The efficiency is, therefore, about 2·5 per cent, and many loud-speakers have only one-tenth of the efficiency of the one quoted. The estimated input power of 0·0005 watt was calculated from experimental data on the R.M.S. current giving the required sound intensity, and on the impedance of the receiver at 800 periods per second.

Mr. H. L. Porter (*in reply*): One conclusion which may be drawn from this discussion is that electrical and acoustical resonance are mainly responsible for distortion in the loud-speaker. The introductory papers, however, were confined to a specialized consideration of one or other of the phenomena, but little attention has been paid to the need for their correlation. The discussion itself did not make this clear. For example, to manipulate the electrical circuit independently of the acoustic system could easily do more harm than good, for one might actually eliminate from the circuit resonances which might be permitted to play a very useful part in a suitably-chosen acoustic system. In our work on the gramophone, we found that the resonance of parts of the system which we anticipated might greatly add to the distortion proved to be very useful in arriving at our curve of uniform distribution of intensity. Again, we found that the greatest distortion did not arise from the separate resonance peaks but from their close acoustical proximity: the orderly arrangement of these peaks was most essential. It therefore seems reasonable to regard the problem of the loud-speaker in a similar manner. If an electrical circuit be used in conjunction with an acoustic system, the combination should be treated as a unit. The contribution of each part of that unit should be ascertained and, if possible, arranged for mutual assistance. In the past, work on the loud-speaker has been mostly concerned with the efficiency of the electrical circuit. There may now be the danger of investigations taking an acoustical bias. Since the final sound waves are determined both by the electrical circuit and by the acoustic system, further work should not be allowed to take what might easily be divergent paths. Our minds must be alert to both considerations.

Professor E. Mallett (*in reply*): In the original telephone receiver and in some loud-speakers the diaphragm performs a double function: it not only provides the necessary vibrating surface which moves the air particles about and so starts a sound wave, but also itself forms the mechanical system which is vibrated by the alternating speech current. In these cases resonance in the diaphragm is doubly important. In

other instruments the vibrating system is a reed or an armature with spring control, each of which will have its own peculiar resonance acting to modify the amplitude of the diaphragm at the point where it is fixed to the vibrating system, but leaving the resonances of the diaphragm still to control the distribution of amplitude over the surface of the diaphragm, and hence the emission of sound waves. In reply to Mr. Burnand, it is thought that these diaphragm resonances will occur whatever the form of the diaphragm, including the cases which he cites.

Many of the speakers have confined their attention to the resonances of the horn, and the various curves exhibited are ascribed to horn resonances. But they are in all cases to be ascribed rather to the combined mechanical resonance of reed (or other vibrator which may be a diaphragm), diaphragm and horn. One speaker, Mr. Nash, shows a curve purporting to separate these out, but the curve is admittedly a theoretical one, and none of the theory is given. But if Mr. Nash's figure for the permissible variation of power output with frequency for no appreciable distortion is correct, i.e. a variation from 100 to 850, or 750 per cent, one might be inclined to ask, "why all this fuss about resonance?" The answer seems to me to be this, that resonance may accentuate unduly a tone which was not originally transmitted. Consider, for instance, an ordinary receiver through the coils of which is flowing a current due to two simultaneously maintained notes at the transmitting end of frequencies $\omega_1/(2\pi)$ and $\omega_2/(2\pi)$. Now let the current be $i_1 \sin \omega_1 t + i_2 \sin \omega_2 t$. The pull on the diaphragm will be proportional to $(B_0 + b_1 \sin \omega_1 t + b_2 \sin \omega_2 t)^2$, where B_0 is the permanent flux, and b_1 and b_2 are the fluxes due to the currents i_1 and i_2. This expression

$$\begin{aligned} = B_0^2 + \tfrac{1}{2}b_1^2 + \tfrac{1}{2}b_2^2 + 2B_0 b_1 \sin \omega_1 t + 2B_0 b_2 \sin \omega_2 t \\ + b_1 b_2 \cos (\omega_1 - \omega_2)t - b_1 b_2 \cos (\omega_1 + \omega_2)t \\ - \tfrac{1}{2}b_1^2 \cos 2\omega_1 t - \tfrac{1}{2}b_2^2 \cos 2\omega_2 t \end{aligned}$$

Thus it is seen that alternating pulls of frequencies $2\omega_1/(2\pi)$, $2\omega_2/(2\pi)$, $(\omega_1 - \omega_2)/(2\pi)$ and $(\omega_1 + \omega_2)/(2\pi)$ are introduced as well as pulls of frequencies $\omega_1/(2\pi)$ and $\omega_2/(2\pi)$ of the original tones. It is true that the amplitudes of the additional pulls are small compared with those of the transmitted tones, provided B_0 is large compared with b_1 and b_2, but they will be appreciable if b_1 and b_2 are increased by overloading the receiver, and the amplitude of the resulting sound wave may be appreciable with quite ordinary loads if the frequency happens to be near a resonance point. With the harmonic tones $2\omega_1/(2\pi)$ and $2\omega_2/(2\pi)$ the resulting effect will probably not be unpleasant, but the summation and difference tones, $(\omega_1 + \omega_2)/(2\pi)$ and $(\omega_1 - \omega_2)/(2\pi)$, may well produce most unpleasant results. This will apply to all those loud-speakers in which there is a permanent magnetic pull on the vibrating system.

Similar considerations apply to the valve if the latter is overloaded, so that either the curved part of the characteristic is used or grid current is allowed to flow. The anode current from a double-frequency E.M.F. on the grid will then contain summation and difference terms which, if they happen to be those of resonance frequencies of the receiver may produce appreciable sound waves. It may also be that with very large sound amplitudes this effect may also appear in the throat of the horn. It would seem possible, therefore, that the question of distortion is more a matter of summation and difference tones than of the relative amplitudes of the transmitted tones. The above considerations would explain satisfactorily why telephone receivers and a loud-speaker worked to give a small sound output give really good reproduction, but that directly the output is increased distortion appears, and the greater the sound output the greater the distortion.

Captain P. P. Eckersley (*in reply*): Mr. Nash has raised the question of the horn. Briefly, the horn gives efficiency, whilst the large-diaphragm, hornless type is inefficient. If, however, the hornless type (for which I hold no brief whatsoever) gives sufficient volume with more faithful quality for an average drawing-room, it has at least served a useful purpose. The particular quality that pleased me in the type of loud-speaker which I demonstrated, was the warmth of bass tones, coupled with an extraordinary faithfulness even in the upper register. This quality might be manifest in a hornless or horn type, the low resonance being in no way intrinsic to the absence of a horn. I still reiterate that what I have called the "efficient" type of loud-speaker with resonances around 1 000 periods per second can never give faithful reproduction, and that lack of warmth in the bass, a minimization of higher harmonics, and a barking of vowel sounds in speech are all characteristic of this type of instrument. Our ears are most sensitive to this middle register, and are asking all the time for stronger extremes of the sound gamut. This must be the next great advance in loud-speaker design; whether the horn will be used or not is immaterial to the question of proper frequency recognition.

PROCEEDINGS OF THE INSTITUTION.

32ND MEETING OF THE WIRELESS SECTION, 7 NOVEMBER, 1923.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 6th June, 1923, were taken as read and were confirmed and signed.

A vote of thanks to Professor G. W. O. Howe for his services as Chairman of the Wireless Section during the past two Sessions was proposed by the President, seconded by Dr. W. H. Eccles, F.R.S., and carried with acclamation.

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Wireless Section, then delivered his Inaugural Address (see page 51).

A vote of thanks to Mr. Shaughnessy for his Address, proposed by Admiral Sir Henry Jackson, G.C.B., K.C.V.O., F.R.S., and seconded by Mr. A. A. C. Swinton, F.R.S., was carried with acclamation, and the meeting terminated at 7.10 p.m.

33RD MEETING OF THE WIRELESS SECTION, 21 NOVEMBER, 1923.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 7th November, 1923, were taken as read and were confirmed and signed.

A paper by Dr. E. V. Appleton, M.A., and Mr. F. S. Thompson, B.A., entitled "Periodical Trigger Reception" (see page 181), and a paper by Mr. R. C. Clinker, Member, entitled "A Dynamic Model of a Valve and Oscillating Circuit" (see page 125), were read and discussed. On the motion of the Chairman a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 7.24 p.m.

704TH ORDINARY MEETING, 22 NOVEMBER, 1923.

[JOINT MEETING WITH THE SOCIÉTÉ DES INGÉNIEURS CIVILS DE FRANCE (BRITISH SECTION).]

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 1st November, 1923, were taken as read and were confirmed and signed.

The President announced that the French Government had awarded to Mr. C. H. Wordingham, C.B.E., and to Mr. Twelvetrees the Diploma of the Officer of Public Instruction, and he asked Monsieur Guéritte, who had obtained the Diplomas from the French Ambassador, to present one to Mr. Twelvetrees, Mr. Wordingham being unavoidably absent.

Monsieur Guéritte then presented the decoration to Mr. Twelvetrees.

A paper by Mr. A. Bachellery, entitled "The Electrification of the French Midi Railway" (see page 213), was read and discussed.

On the motion of the President a vote of thanks to the author was carried with acclamation. The meeting terminated at 7.50 p.m.

705TH ORDINARY MEETING, 29 NOVEMBER, 1923.

(JOINT MEETING WITH THE PHYSICAL SOCIETY OF LONDON.)

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 5.30 p.m.

The minutes of the Ordinary Meeting of the 22nd November, 1923, were taken as read and were confirmed and signed.

A discussion took place on "Loud-Speakers for Wireless and other Purposes," in connection with which the following introductory papers were read (see pages 265 to 285):—

Prof. A. O. Rankine, D.Sc.: "General Principles involved in the Accurate Reproduction of Sound by means of a Loud-Speaker."

Mr. L. C. Pocock, B.Sc.: "Theory of Loud-Speaker Design."

Prof. C. L. Fortescue, M.A.: "The Sources of Distortion in the Amplifier."

Mr. H. L. Porter, B.Sc.: "The Acoustic Problems of the Gramophone."

Mr. E. K. Sandeman, B.Sc.: "The Relative Importance of each Frequency Region in the Audible Spectrum—Measurements on Loud-Speakers."

Prof. J. T. MacGregor-Morris and Prof. E. Mallett, M.Sc. (Eng.): "The Overtones of the Diaphragm of a Telephone Receiver."

Mr. G. A. Sutherland, M.A.: 'Auditorium Acoustics and the Loud-Speaker."

Mr. S. G. Brown, F.R.S.: "Some Directions of Improvement in the Loud-Speaking Telephone."

Captain P. P. Eckersley: "The Characteristics of a New Type of Loud-Speaker."

The discussion was adjourned and the meeting terminated at 9.40 p.m.

34TH MEETING OF THE WIRELESS SECTION, 5 DECEMBER, 1923.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 21st November, 1923, were taken as read and were confirmed and signed.

A paper by Mr. L. B. Turner, M.A., Member, entitled "The Relations between Damping and Speed in Wireless Reception" (see page 192), was read and discussed. On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.40 p.m.

706TH ORDINARY MEETING, 13 DECEMBER, 1923.

(Held in the Institution Lecture Theatre.)

Professor E. W. Marchant, D.Sc., Vice-President, took the chair at 6 p.m., in the unavoidable absence of Dr. A. Russell, President.

The minutes of the meeting of the 29th November, 1923, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A paper by Mr. D. Brownlie, B.Sc., entitled "Pulverized Fuel and Efficient Steam Generation," was read and discussed. On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.55 p.m.

35TH MEETING OF THE WIRELESS SECTION, 2 JANUARY, 1924.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 5th December, 1923, were taken as read and were confirmed and signed.

A paper by Mr. R. H. Barfield, M.Sc., Student, entitled "Some Experiments on the Screening of Radio Receiving Apparatus" (see page 249), was read and discussed. On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.10 p.m.

707TH ORDINARY MEETING, 3 JANUARY, 1924.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 13th December, 1923, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

The following list of donations was taken as read and the thanks of the meeting were accorded to the donors:

Benevolent Fund: W. H. Bottomley; R. V. Broberg; C. Cartmell; T. C. Christianson; E. T. Clifford-Jones; A. C. Coward; H. J. Finder; F. W. Geoghegan; P. H. Gwynn; Messrs. W. T. Henley's Telegraph Works; T. W. E. McKew; W. G. P. Mitchell; F. Riley; W. G. Smith; and The "Twenty-five" Club (per Mr. W. B. Esson).

Dr. S. P. Smith, Member, then delivered a lecture entitled "Railway Electrification in Foreign Countries" (see page 317), and the lecture was followed by a discussion (see page 322). On the motion of the President a vote of thanks to the lecturer was carried with acclamation, and the meeting terminated at 7.45 p.m.

708th ORDINARY MEETING, 10 JANUARY, 1924.

[Joint Meeting with the Société des Ingénieurs Civils de France (British Section).]

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 3rd January, 1924, were taken as read and were confirmed and signed.

The discussion on Mr. A. Bachellery's paper entitled "The Electrification of the French Midi Railway" (see page 213), was continued, and the meeting terminated at 7.25 p.m.

709th ORDINARY MEETING, 17 JANUARY, 1924.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 10th January, 1924, were taken as read and were confirmed and signed.

Messrs. A. H. Allen and A. T. Dover were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows:—

Elections.

Members.

Aitken, Robert.
Cornfoot, Thomas.
Kennedy, Peter.
Kirkland, John Wilkinson.
Prince, Charles Edmond, Major.
Street, Charles Frederick.

Associate Members.

Adendorff, Gerald Victor.
Barnard, Frederick George.
Bowen, James Bevan, Wing-Commander R.A.F.
Brown, Cecil Norman.
Davies, Ralfe Davidson, Lieut. R.E.
Gage, Ernest Cecil.
Galliard, John Douglas.
Glanville, George Grosvenor.
Kendon, Donald Henry.
Lewtey, William Cruchley.
Mayral, Arthur Lawrence G.
Ohtsuki, Takashi.
Rawlinson, Rowland Henry.
Ricci, Ralph Elwyn.
Rissik, Jacob Willem, B.Sc. (Eng.).
Sheldrick, John Engledow, B.Sc. (Eng.).
Smith, Arthur Eric, B.Sc. (Eng.).
Smith, Ronald.
Struthers, George Alexander.
Tilley, Herbert Benjamin.
Toogood, Henry Featherston.
Varadachari, Perungavin.
Wilson, Herbert.
Workman, Eric Walter, B.Sc. (Eng.).

Graduates.

Ashton, William Thomas.
Atherton, John Francis.
Bickerstaff, Ernest.
Birkby, Harold.
Bliss, William Arthur.
Burn, Walter.
Carter, Arthur.
Close, Charles Victor.
de Burgh, Desmond, Herlouin, Flight Lieut. R.A.F.
Duce, George William, B.Sc. (Eng.).
Earle, Beresford Langston.
Eggins, Leonard George.
Forrester, James Shannan.
Garrett, Percival Theodore.
Ghosh, Surendra Nath.
Gill, Ernest William.
Glass, Francis.
Gould, Frank.

Graduates—continued.

Grainger, Oliver.
Groser, Stanley Rust.
Hall, John, B.Sc. (Eng.).
Hay, Andrew.
Henzell, George Peregrine.
Hewitson, Maynard.
Hounsell, Ernest Alfred.
Hughes, Lionel Jutson.
Kaempf, Emil.
Langlands, George Boyd.
Lucas, Leonard Hillyer.
Lundy, George Alfred.
McLaughlin, Bernard Alphonsus.
Mayo, Oswald James.
Mill, Harry.
Mitchell, George William.
Munro, John.
Nicholes, Samuel.
Nixon, Thomas Edgar B.
Osborn, Thomas Lester A.
Pearce, Reginald.
Pollack, Leonard Austin.
Pound-Corner, Harold Sinclair, B.A.
Procter, William Skirrow.
Scott, Alexander Theodore.
Sinclair, Harold.
Smith, Hubert Alfred, B.Sc.
Tozer, Robert James M.
Valentine, Arnot Stirling.
Verma, Panna Lal.
Wells, Charles Frederick.

Students.

Adbûtharaj, Rajiah.
Aiken, Leslie James.
Allcock, Frank Byard.
Anderson, Frank Cordue K.
Anderson, James Peter.
Anderson, Savile.
Andrews, Allan.
Archer, Leslie John.
Aria, Dadiba.
Atkins, James Walter.
Attlee, John Stuart.
Austen, Donald Edwin H.
Austin, Percy Ellis, B.Sc. (Eng.).
Azimuddin, Mohamed.
Bagnall, Maurice Arthur.
Bagshawe, Alexander Sinclair.
Baker, Ernest Edward.
Baldwin, Cecil Spence S.
Ball, William Barnard, B.Sc.
Banbury, Leonard Glanville.
Banks, Rowland Victor.
Bannatyne, Andrew Mansfield.
Bartlett, Cecil Vernon.
Batten, Ernest Richard.
Batty, Bernard.
Beer, Horace George.
Behrman, Boris.
Bell, Ian.
Bertone, John.
Bishop, John Montague, B.E.
Bogie, Andrew.
Bowden, George Herbert.
Boyne, John Grant.
Braid, Kenneth Edwin P.
Brailsford, Fred.
Brewer, Arthur Ernest.
Brierly, Richard Francis H.
Brown, Robert Redman.
Bull, Malcolm James.
Bush, Alfred John.
Cade, Sydney George.
Canning, Horace Reginald.
Carfrae, William John.
Carter, Murray Oliphant.
Catchatoor, George Eardley A.
Chapman, Geoffrey Tancock.
Chenevix-Trench, Lionel Geoffrey.

Students—continued.

Chisnall, Cecil Ernest.
Church, John William G.
Cleveland, George Robert E.
Cobb, Kenneth.
Cochran, Robert Jack.
Cokart, Petrus Isaac.
Cole, Frank Jaspar.
Colmar, Geoffrey Charles.
Connolly, Reginald Charles H.
Cook, Albert Edwin.
Cooke, Norton Robson.
Cooper, George Frederick.
Cox, Albert Rowland.
Crawshaw, Cyril John, B.Sc. (Eng.).
Crisp, Arthur Bright.
Cronwright, Roy Bazett, B.Sc.
Cullimore, Cedric Anthony.
Damant, George Edward.
Davidson, William Stewart.
Davoren, Lucius Andrew.
Dicks, William John H.
Dodd, John Hedley.
Dunbar, James Quentin.
Dupen, Vivian Cecil.
Easton, Nigel Tytherleigh.
Esther, Harry, B.Eng.
Field, James Frederick.
Fenton-Jones, Hugh.
Fletcher, Dudley Wilfred H.
Fox, Kenneth McLean.
Freeland, Arthur James.
Freeman, Charles Frederick.
Fricke, Henry Moger.
Frugtniet, Adalbert Vance.
Gardner, James Nielson.
George, Henry Hale.
Gibson, Robert.
Godden, William Fenwick.
Gomez, Jose Gomez.
Good, William Rexter.
Goubert, Arturo.
Graham, Douglas Ernest.
Graham, Harry.
Grant, Allan, B.Sc.
Green, Harry.
Griffith, Herbert Clewin.
Grove, George Richard P.
Hall, John Lawrence.
Hampshire, Harold William T.
Hancock, Harold Percy.
Hards, Richard Leo.
Harper, William George.
Harris, Francis Alfred.
Harris, Richard H.
Harrison, John Murray.
Harvey, Hector Gordon.
Haskard, John Leslie.
Heap, David, B.Sc.Tech.
Hedley, Hugh Hutton.
Hedley, Isaac Herdman.
Henry, Howard Francis.
Higgs, Thomas Ware.
Hinds, James Oliver.
Hinnawy, Abdul Magid.
Hodges, Leonard Allen.
Hogarth, John Russell.
Hogbin, Archibald.
Hollingshead, John.
Holmes, John Hardy.
Hughes, Alexander Russell M.
Hughes, Charles Wesley.
Hughes, Julio Reginald.
Hughes, Thomas Charles.
Hunking, Arthur Lancelot.
Hunter, Kenneth Kirkwood.
Hutchings, Eric Edward.
Jacques, John Rowland.
Jarvis, Arthur Porter.
Jehu, John William.
Jesty, Edgar Henry.
Jewsbury, Eric.
Jewsbury, William.
Johnston, Eric Montague.
Jones, Frank, B.Sc.
Kalle, Maurice L. F.
Kingshott, George William.
Kirkby, Norman Reginald.
Kirsten, Kenneth Haenert, B.Sc.
Knight, Arthur William.
Lamb, Henry Lincoln.
Lane, Francis John, B.Sc.
Latham, Tom.
Lawrence, Alan.
Lessel, Robert James.
Lightbown, John.
Linton, James.
Lloyd, John Austin H.
Long, Geoffrey.
Lower, John Henry.
McClean, Herbert George, B.Sc. (Eng.).
McClure, Charles Archibald.
McCracken, Stanley.
McFarlane, John.
Macfie, Duncan Brown.
McGavin, James.
Mackenzie, Evan John.
Mackenzie, William Alexander.

Students—continued.

McKie, David Gordon.
McLean, Francis Charles.
Manning, James Walter G.
March, Charles Edward M.
Matthews, Albert Dent.
Matthews, Harry James.
Maye, John Wintle.
Mayhew, Thomas Alfred.
Meares, Oswald Mapletoft.
Meneze, John Arthur.
Milne, Alexander James.
Mitchell, Alexander.
Mitchell, Ernest James W.
Moller, Herbert Cecil H.
Morton, Harold Christopherson.
Mosedale, Philip John.
Motha, Britto Raphael.
Moursi, Mostafa Riad.
Mullineux, James.
Nagel, Llewellyn.
Nahapiet, Ernest Owen.
Nash, Alfred James L.
Nind, Eric Arthur.
Nottingham, Edward Charles.
Ogden, Horace Chadwick, B.Sc. (Eng.).
Old, David.
Oldcorn, Eric Carlton T., B.Sc.
Olver, George Corden.
Osborn, Leroy Gordon.
Parish, William Joseph.
Parsons, Henry Harold.
Passmore, Charles Rivers.
Pattinson, Robert Raine.
Paul, Jack Heron.
Peakin, Cecil John.
Pearson, Frederick John.
Peasgood, Harold.
Peckett, Leslie James.
Perkins, Griffith Hugh, B.Sc.(Eng.).
Phillips, John Leslie.
Phillips, John Waldron.
Pilfold, Charles William.
Plumtree, Ian Stanley.
Porter, Andrew.
Price, Gilbert Watts.
Pritchett, Cyril George.
Pye, Frank Peveril.
Radford, John Samuel.
Ragunather, Arumugam.
Record, Charles Reuben.
Reid, William Alfred.
Renwick, William John.
Revell, Edward Walter M.
Ridsdale, Henry Arthur C.
Ritchie, Henry Wilfred.
Robertson, Gilbert.
Rogerson, Richard Wyndham.
Roseway, Walter Norman.
Rowell, Cecil Victor.
Russell, John Joseph.
Sanders, Arthur Leslie.
Sanderson, Albert King.
Schiodt, Martin Theodore.
Scott, Eric Kenneth.
Shaw, Cecil Maurice.
Shearer, James.
Shurben, Henry William J.
Sicling, Reginald Harry.
Sieveking, Herbert.
Simpson, George Francis.
Simpson, Norman George.
Skinner, Frederick George J.
Smith, David Hughes.
Smith, David Salmond.
Smith, Eustace Herbert.
Smith, Frank Jervis.
Smith, Ian Stewart.
Smith, Thomas Haworth.
Smythe, Francis Sydney.
Spindler, Arthur Hardman.
Squires, Frank Henri.
Starling, Benjamin.
Stewart, Ian Dunlop.
Storer, Robert Harrison.
Striem, Hubert Henry V.
Symes, George Leslie.
Tannett, Anthony.
Taylor, Samuel Mellor.
Tetley, Arthur Cyril.
Thomas, Arnold Harrison.
Thomas, Edgar Frank E.
Thornton, James Philip.
Tibbitts, Edgar Ernest.
Tidmus, Allan Hinds.
Todd, William George.
Trimmer, William Jack.
Tuck, William Douglas.
Tufnail, Maurice Edward.
Vallis, Leslie Cecil.
Verano, Ernest Augustus.
Vernier, Charles Leonard.
Vickers, Harold Edwin.
Villiers, William Amherst.
Walsh, Joseph Anthony.
Waterfield, Henry (Jnr.).
Watson, Robert Parker, B.A.
Watt, Warden Kennedy.
Webb, John Krauss.
Weston, Gordon.
Wheatley, Stanley James.
White, Jack.
Williams, Joseph.
Wills, David Hilary.

Students—continued.

Wilson, James.
Windred, George.
Witt, Stanley Reuben.
Wittrick, James Lewis.
Woodbridge, Arthur William.
Woodcock, Vincent.
Woodcock, Walter Leslie.
Woodforde, John.
Worthing, Cyril Evans.
Young, Albert Edward.
Young, Norman James.
Young, Richard Vincent.

Associates.

Atherton, Arthur.
Owles, Archibald Bewick.
Tansley, George Edward.

TRANSFERS.

Associate Member to Member.

Farrow, Alfred Edward.
French, Walter William E.
Gittins, George Edward, B.Sc.
Handley, Benjamin.
Harrison, Harry Hughes.
Lawson, Walter.
McLennan, Duncan.
Martin, Harold.
Mayes, Arthur Edward.
Naylor, William Slater.
Nelson, James.
Newberry, William George.
Phillips, Lewis Waight.
Stigant, Stanley Austen.
Thompson, Harry Sydney.
Waygood, Oscar Candish.
Wilcox, Walter Maitland, B.Sc.(Eng.).
Wilson, Henry.

Associate to Member.

Short, Frederick Martin.

Graduate to Associate Member.

Boyland, Harold John.
Bremner, Francis Donald H., B.A.
Brigg, John Ellwood.
Edwards, Leslie.
Farrell, James Fraser E.
Peasgood, Frank.
Searles, Harold Everard.
Smith, Esmond Wassell.
Smith, Harry Foster.
Stinchcomb, Ernest Arthur.
Swift, Bernard.
Vanneck, Richard Grant, M.C.
Waddicor, Harold, B.Sc.
West, Frederick William J.
Willson, Charles Schummelketel, B.Sc.(Eng.).

Student to Associate Member.

Benger, William Alan.
Buckman, Henry Leonard, B.Sc.
Chadwick, Samuel.
Champney, Laurence.
Hall, William Noel.
Hoyle, William Dickon.
Moir, Roy Adamson.
Morgan, Percy Davies.
Nicholson, Graham Franklin.
O'Neill, James Francis.
Perks, John Noel R.
Scott-Taggart, John, M.C.
Serner, Arthur.
Villiers, Algernon Edward, M.A.

Student to Graduate.

Beckett, Charles Murray.
Berry, John.
Booth, John Arthur.
Bulley, Henry Samuel.
Burgess, William.
Capper, Frank Wilton.
Chakravarti, Girindra Narayan.
Clarke, Harold.
Coates, Albert William.
Corkill, William Alfred.
Corner, Herbert.
Ganapati, Salem Vencatramana.
Gaster, Abraham Emmanuel.
Henderson, Francis Adrian.
Hine, Frank Walter.
Hipwell, James Henry.
Hobson, Ralph Silvanus.
Horowitz, Hyman.
Howard, Henry John.
Hutton, William Stanley.
Jordan, William Stewart.
Leathes, William Henry B.
Lissenden, Percival Horace.
McEwan, John Douglas T.
Mackay, William Morton.
McKnight, William Alexander.
McNab, John.
Omar, Sidiqi Mohamed.
Payne, Charles Jeffery.
Pennal, Herbert William.
Sanderson, Edward Robson.
Small, Allan Jamieson.
Snipe, Norman Victor.
Stansfield, Joshua Bertram, B.Sc.(Eng.).
Thompson, Cecil George.
Torrance, John.
Tucker, John Potterton.
Wade, John Charles.
Wilson, David MacArthur.

A paper by Mr. H. Marryat, Member, entitled "Electric Passenger Lifts" (see page 325), was read and discussed. On the motion of the President a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.47 p.m.

710TH ORDINARY MEETING, 31 JANUARY, 1924.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 17th January, 1924, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A list of donations to the Benevolent Fund (see pages 210 to 212) was taken as read and a vote of thanks was accorded to the donors.

The President announced that the third award of the Faraday Medal had been made to Dr. S. Z. de Ferranti, Past President.

A paper by Professor W. M. Thornton, O.B.E., D.Sc., Member, entitled "Some Researches on the Safe Use of Electricity in Coal Mines," was read and discussed. On the motion of the President a vote of thanks to the author was carried with acclamation and the meeting terminated at 7.52 p.m.

36TH MEETING OF THE WIRELESS SECTION, 6 FEBRUARY, 1924.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 2nd January, 1924, were taken as read and were confirmed and signed.

A paper by Mr. E. B. Moullin, M.A., Member, entitled "Atmospherics and their Effect on Wireless Receivers" (see page 353), was read and discussed. A vote of thanks to the author was carried with acclamation and the meeting terminated at 7.50 p.m.

INSTITUTION NOTES.

Coopers' Hill War Memorial Prize.

The prize for the year 1922 (see *Journal I.E.E.*, 1921, vol. 59, p. 346) has been awarded to Mr. F. R. Combes for his monograph on "An Historical and Critical Survey of Atmospheric Electricity and Protection against Lightning."

"Chartered Electrical Engineer."

The following Bye-law of the Institution (in substitution for existing Bye-Law 9), which was adopted at a Special General Meeting of the Corporate Members held on the 28th February last, was allowed by the Lords of His Majesty's Most Honourable Privy Council on the 20th March, 1924:—

(*a*) An Honorary Member shall be entitled to the exclusive use after his name of the initials "Hon. M.I.E.E."; a Member of the initials "M.I.E.E."; an Associate Member of the initials "A.M.I.E.E."; an Associate of the initials "Associate I.E.E."; a Graduate of the initials "Graduate I.E.E."; and a Student of the initials "Student I.E.E."

(*b*) Every Member and Associate Member is, and is entitled to describe himself as, a Chartered Electrical Engineer, and in using that description after his name shall place it after the designation of the class in the Institution to which he belongs, stated in accordance with the following abbreviated forms, namely, M.I.E.E. or A.M.I.E.E., as the case may be.

(*c*) A Member or Associate Member practising
- (i) under the title of, or as an officer or employee of, a Limited Company authorized to carry on the business of an electrical engineer in all or any of its branches, or
- (ii) in partnership with any person who is not a Member or Associate Member of the Institution under the title of a Firm

shall not use or permit to be used after the title of any such Company or Firm the designation "Chartered Electrical Engineer" or "Chartered Electrical Engineers" or describe or permit the description of such Company or Firm in any way as "Chartered Electrical Engineer" or "Chartered Electrical Engineers."

(*d*) No person shall adopt or describe himself by any other description or abbreviation to indicate the class to which he belongs than is provided in this Bye-law for such class.

National Certificates and Diplomas in Electrical Engineering.

The following is a further list of schools and colleges approved for the award of the above [see *Institution Notes*, No. 39, page (18), July 1923, and *Journal I.E.E.*, 1924, vol. 62, page 209].

Approved for Ordinary Grade Certificates (*Senior Part-time Courses*).

Aston Technical School.
Bootle Municipal Technical School.
Darlington Technical College.
Dewsbury Technical School.
Doncaster Technical College.
Dudley Technical College.
Handsworth Technical School.
Hanley Technical School (Stoke-on-Trent).
Huddersfield Technical College.
Hull Municipal Technical School.
L.C.C. School of Engineering and Navigation.*
Leeds Central Technical School.
Manchester College of Technology.
Oldham Technical School.
Portsmouth Municipal College.
Sheerness Technical Institute.
Sheffield University.
Stoke-on-Trent Central School of Science.
Swansea Technical College.

Approved for Higher Grade Certificates (*Advanced Part-time Courses*).

Halifax Technical College.
L.C.C. School of Engineering and Navigation.*
Liverpool Central Technical School.
Manchester College of Technology.
Portsmouth Municipal College.

Approved for Ordinary Grade Diplomas (*Senior Full-time Courses*).

Leeds Central Technical School.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 February to 25 March, and of those paid direct to the Institution bankers from 1 January to 25 March, 1924:—

	£	s.	d.
Alabaster, Bt.-Major E. O. (Gosport) ..		5	0*
Allen, A. H. (London)	1	1	0*
Allom, G. F. (London)	1	1	0*

* Annual Subscriptions.

* Shown on page 210 of *Journal* No. 326 (February 1924) as "Poplar School of Navigation."

	£	s.	d.
Arnold, K. N. (Purbrook, Hants)		10	6*
Atkinson, Ll. B. (London)	1	0	0*
Austin, H. S. E. (Norwich)	1	1	0*
Aylott, H. J. (Ilford)		10	0*
Baker, C. J. (London)		10	6*
Barlow, Edwin (London)		2	6*
Barnard, A. G. S. (Liverpool)		5	0*
Barnes, A. S. (Oxford)		10	0*
Bastable, H. A. (Japan)		10	6*
Batt, F. H. (Manchester)		5	0
Baxter, E. H. (London)		5	0*
Bean, J. S. (Crewe)		5	0*
Beavis, E. A. (London)		5	0*
Bedford, R. (Leicester)		5	0*
Beeton, S. (Weybridge)	1	1	0*
Benn Bros., Ltd. (London)	2	12	6
Bennett, A. E. (Selangor, F.M.S.)	1	0	0*
Bennett, T. C. (Wakefield)		10	0
Blennerhassett, R. F. P. (London)		10	0*
Boraston, C. A. (Warlingham)	1	0	0*
Bowden, J. R. J. (London)		5	0
Bown, F. J. (Hebburn-on-Tyne)		5	0*
Briant, F. G. (Helsby)		10	0*
Briggs, E. E. (London)		10	0*
Brookes, R. C. (Liverpool)	1	0	0*
Brousson, R. P. (London)	2	2	0*
Brown, J. S. (Southampton)		10	0*
Brown, Walter (Hong-Kong)		15	0*
Brown, Brig.-General W. Baker (Ashtead)	1	0	0*
Browne, B. F. (Santos, Brazil)	1	5	0
Brownjohn, W. H. (London)	1	1	0*
Bulow, V. A. M. (Glasgow)		5	0*
Burbridge, W. C. (Birmingham)		5	0*
Burgess, A. F. (London)		10	0*
Burnand, W. E. (Sheffield)	2	2	0*
Burns, John (Leeds)		5	0*
Burton, W. (Birmingham)		12	6*
Buttenshaw, H. F. (Wakefield)		10	0
Caine, L. E. (Kenya Colony)		10	0*
Campion, R. H. (Chesterfield)	1	1	0*
Carden, Lt.-Col. A. D. (Aldershot)		5	0*
Carpenter, G. W. (Scarborough)		5	0
Carrick, J. H. (Leeds)		6	6*
Carter, A. F. (Leeds)		10	0*
Cash, H. J. (London)		10	0
Channon, H. C. (London)		10	0*
Chartres, C. B. (Calcutta)		10	6*
Chattock, R. A. (Birmingham)	1	1	0*
Chaytor, A. R. (Chesterfield)		12	6
Cheetham, G. A. (Manchester)		10	0*
Clack, C. W. (London)		15	0
Clark, E. Fowler (Derby)		2	6*
Clayton, B. C. (Edinburgh)		10	6*
Clifford-Jones, E. T. (Colenso, Natal)		2	6
Clinton, W. C. (London)		10	6*
Clothier, H. W. (Wallsend-on-Tyne)		10	6*
Colebrook, H. F. (Guildford)	1	1	0
Constable, A. D. (Oxted)	1	0	0*
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Cowie, J. R. (London)	1	1	0*

* Annual Subscriptions.

	£	s.	d.
Cox, C. H. F. (London)		10	6
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Dalton, J. C. J. (London)		5	0*
Darby, B. (Manchester)		10	0*
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Davies, James (Eccles)		5	0*
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Digby, T. J. (London)	2	2	0*
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Ebner, P. C. (London)	1	1	0*
Eccles, Dr. W. H. (London)	1	0	0*
Edgcumbe, Lt.-Col. Kenelm (London)	1	1	0*
Emerson, S. J. (Chester)		3	6
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Faulkner, H. (St. Margaret's, Middlesex)		2	6*
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Fox, H. C. (Birmingham)		5	0
Freedman, P. (London)		5	0
Friendship, C. A. (Runcorn)		5	0
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Hardy, R. (Lowestoft)		7	6*

* Annual Subscriptions.

	£	s.	d.
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Hawkins, G. C. (Kew)	1	1	0*
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Head, W. J. (Newcastle-on-Tyne)		5	0*
Hegney, V. J. (Glasgow)		5	0*
Henderson, J. (Belvedere)		5	0
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Holmes, Stratten (Bristol)		5	0*
Holttum, W. (Birkenhead)		5	0*
Horne, W. F. M. (Braintree)		2	6*
Houstoun, R. F. H. (Wallsend-on-Tyne)	1	0	0*
Howard, A. J. (Taunton)		5	0*
Hughes, C. T. (London)		5	0*
Hunter-Brown, P. (London)	1	1	0*
Hutton, F. W. (Frodsham)		5	0*
Informal Meetings Smoking Concert	8	12	8
Jacob, E. S. (London)	1	1	0*
Jago, R. A. (Chertsey)		2	0
James, E. W. (Hounslow)		10	6*
James, W. L. (Cardiff)		5	0*
Jeffery, L. B. G. (Grimsby)		5	0*
Jewson, F. K. (London)		5	0
Johnson, J. H. (Chelmsford)	1	1	0*
Jolliffe, V. N. (Penarth)		2	6*
Jones, A. T. (London)		4	0
Jones, Christopher (Walsall)		10	6*
Kelly, A. C. (Buenos Aires)	1	1	0*
Kennedy, Sir Alexander (London)	10	0	0*
Kennedy-Purvis, Captain C. E. (London)		15	0*
Kennett, A. J. N. (London)		10	0*
Kenworthy, A. (Chatham)		5	0*
Kingsbury, H. (London)	2	2	0*
Kingston, Major J. R. (London)		10	0*
Kolle, H. W. (London)	2	2	0*
Langdon, G. H. (Weston-super-Mare)	1	1	0*
Lash, A. R. (Falkland Isles)		5	0*
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Mead, R. H. (London)		5	0
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* Annual Subscriptions.

	£	s.	d.
Medlam, W. B. (London)		10	0*
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Minshall, Colonel T. H. (London)	1	1	0*
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Morecombe, W. M. N. (Gosport)		10	6*
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Nelson, C. W. G. (Birmingham)		5	0*
Nelson, J. E. (Runcorn)	1	0	0*
Nelson, R. (Harpenden)	1	1	0*
New, C. G. Morley (Cardiff)		5	0*
Newell, C. A. (Blackheath)		10	0
Newman, A. S. (Uxbridge)		5	0*
Nielson, J. F. (Glasgow)		10	0*
Nobbs, C. G. (London)		10	6*
Noddings, W. B. (Manchester)		2	6*
O'Brien, B. H. (London)		5	0*
Ogilvie, Colonel Sir Andrew (London)	1	1	0*
Oliver, C. (London)	1	1	0*
Oliver, V. F. M. (Sunninghill)		5	0*
Otter, F. L. (Johannesburg)	1	0	0*
Palmer, A. H. (Darlington)		5	0*
Parker, Harry (Porth, Glam.)		5	0*
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Partridge, G. W. (London)	2	2	0*
Patchell, W. H. (London)	1	0	0*
Pate, W. (Carnoustie)	1	1	0*
Payne, F. G. (Rhodesia)	1	1	0*
Pender, D. (Liverpool)		10	0*
Perry, C. S. (Dublin)		5	0*
Piggott, J. W. (Whitby)		5	0*
Preece, A. H. (London)	2	2	0*
Prentice, H. Napier (Stowmarket)	1	1	0*
Price, L. (Lytham)		5	0*
Puckle, O. S. (London)		2	6
Pyne, A. P. (Newcastle-on-Tyne)		10	6*
Rich, T. (London)		10	6*
Richards, H. W. H. (London)	1	5	0
Ripley, D. (Edinburgh)		10	0*
Rivers-Moore, H. R. (Croydon)	1	0	0*
Robb, Dr. A. A. (Belfast)	2	12	6
Roberts, Alfred (London)		10	6
Robertson, J. A. (Manchester)	1	1	0*
Robertson, R. (Glasgow)	1	1	0*
Robinson, B. A. (Hexham-on-Tyne)		5	0*
Rogers, H. I. (Bath)		15	0*
Roget, S. R. (London)	1	1	0*
Roles, T. (Bradford)		9	6*
Rosling, P. (London)	2	2	0*
Ross, G. (London)		2	6*
Rosser, G. L. (Bolton)		10	0*
Russell, Stuart A. (London)	1	1	0*
Saddington, C. W. (Oban)		10	0*
Saunders, H. S. (Yeovil)		2	6*
Sayers, Josiah (Derby)	1	1	0*

* Annual Subscriptions.

	£	s.	d.
Scott, W. H. (Norwich)	1	1	0*
Selvey, W. M. (London)		12	6*
Shakeshaft, F. (Coventry)		10	0*
Sharp, D. C. (Westbury)		10	0*
Shaw, W. B. (Manchester)	1	1	0*
Shipley, J. F. (Valparaiso)	2	2	0*
Shires, G. E. (Doncaster)		8	6
Simpson, F. A. (Newmarket)		10	6*
Simpson, M. G. (Tunbridge Wells)		10	6*
Siviour, S. R. (Mirfield)		5	0
Skelton, H. A. (Foyers, Inverness) ..	1	0	0*
Slee, Commander J. A. (London)		15	0*
Slingo, Sir William (London)	1	1	0*
Smith, Prof. S. P. (Glasgow)	1	1	0*
Smith, W. G. (Croydon)		10	6
Smyth, C. H. (London)	1	1	0*
Snell, Sir John (London)	1	1	0*
Snell, J. B. (London)	1	5	0*
Southern, J. H. (Redcar)	1	0	0*
Spary, P. G. (Southampton)		5	0
Spencer, W. G. (London)	1	1	0*
Stewart, A. C. (Glasgow)		5	0*
Stewart, C. (London)	1	0	0*
Stocken, E. C. (Lingfield)		10	6
Streatfeild, Rev. R. H. (Sevenoaks) ..		10	0*
Strickland, A. (Colombia, S. America) ..		7	6
Stubbs, A. J. (London)	1	0	0*
Sullivan, H. W. (London)	2	2	0*
Swale, W. E. (Hanley)		10	0*
Swire, W. H. T. (Dundee)		10	6*
Targett, J. H. (Llanrwst, N. Wales) ..		10	0*
Tasker, E. E. (Brentwood)	1	1	0*
Tennant, N. S. (Hexham-on-Tyne)	1	11	0*
Thomas, H. J. S. (Middlesbrough)		5	0*

* Annual Subscriptions.

	£	s.	d.
Thomas, T. R. (Cardiff)		5	0*
Thomas, T. S. (Bargoed, Glam.)		5	0*
Thompson, N. A. (Beyris, France)		5	0*
Thorn, C. H. R. (Calcutta)	1	0	0*
Trench, R. C. (Westerham)		10	0*
Turner, E. O. (Birmingham)		15	0
Turner, John (Hollinwood)		5	0*
Turner, John Wm. (London)		7	6*
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Vaughan, C. J. (Birmingham)		10	6*
Walker, Prof. Miles (Buxton)	1	1	0*
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Wardrobe, F. (Sheffield)		10	6*
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Wilson, G. H. (London)		5	0
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Wilson, W. (Birmingham)		10	6*
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PULVERIZED FUEL AND EFFICIENT STEAM GENERATION.

A DETAILED CONSIDERATION OF THE PERFORMANCE OF PULVERIZED FUEL AS COMPARED WITH MECHANICAL STOKING UNDER THE MOST MODERN CONDITIONS.

By David Brownlie, B.Sc.

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Summary.

The paper is a detailed consideration of the latest developments in the use of pulverized coal for steam generation, and a comparison of the advantages and disadvantages of this method of firing as compared with mechanical stoking, in each case under the latest improved conditions and more particularly as applied to very large power-station boiler plants. Since the starting up in December, 1920, of the pioneer large installation, Lakeside, Milwaukee (40 000 kW on Lopulco pulverized fuel), the progress made in the United States has been remarkable, and approximately 3 500 000 tons of pulverized coal per annum will shortly be burnt under water-tube boilers.

The paper contains a full account of the Lakeside station, particularly the exact working costs, whilst a description is also given of the River Rouge plant at Dearborn, Detroit, as representatives of modern pulverized-fuel practice. For comparison, a similar account is given of the Dalmarnock power station, Glasgow, characteristic of the best British mechanical stoker practice.

The author is of the opinion that the advantages in the aggregate of pulverized fuel are so great that they constitute almost a revolution in steam-boiler practice. The paper also contains a large amount of general statistical matter.

Introduction.

One of the most striking developments in the whole history of steam generation has been the rapid growth of the use of pulverized fuel in the United States during the past three or four years.

This progress is so remarkable, alike in the net working efficiency obtained, the size of the individual boilers made possible, and the use of the most modern methods of scientific control of the working of the boiler plant, practically from a distant switchboard, that something like a revolution in steam practice has undoubtedly been effected.

In view of the importance of efficient steam generation, both in power station work and from the national point of view, the most serious consideration in Great Britain of the whole question of pulverized fuel is, in the author's opinion, imperative.

In the present paper the author has endeavoured to give a survey of the latest developments in the use of pulverized fuel for steam generation. On account of the somewhat controversial nature of the whole question and the great difficulties in the way of comparing two entirely different systems of firing, i.e. pulverized fuel and mechanical stoking, because of almost endless complications due to load factor, price and quality of fuel, fluctuations in steam demand, and varying rates for labour, all of which cloud the issue, the author has based the paper on the performance of one definite pulverized-fuel plant, that of the Lakeside station, of the Milwaukee Electric Railway and Light Company, on Lake Michigan.

This plant is in the first place the pioneer modern large steam-generation plant fired with pulverized fuel, and it has the advantages—from the point of view of the power station engineer—that it is a generating station of very large size, viz. 40 000 kW, which has been running nearly three years, whilst the most elaborate records, almost unique in their thoroughness, have been taken of every detail of the performance. Also it is what would be termed to-day a "low-capacity" and "central" pulverized-fuel plant, which is to the advantage of mechanical stoking in the comparison, as distinct from high-capacity plants, such as those at Cahokia, Cleveland, Vitry, and Trenton Channel.

With regard to Lakeside, the author has been given the opportunity by Mr. John Anderson, the chief engineer, through the kindness of Mr. W. R. Wood, managing director of the Underfeed Stoker Co., Ltd., of studying the remarkable records obtained at this station. They include not only the efficiency of the plant and the exact cost of drying, pulverizing, and generally preparing the fuel, together with the wages bill and the repair and maintenance costs, but, in addition, even such difficult items as the actual amount of excess air required in the combustion. All these different figures have not hitherto been published under one head, and together they give reliable and extensive data on the performance of pulverized fuel (as applied to steam generation under given definite conditions) of a kind that has not before been easily available.

The author has not included any reference of importance to the so-called "unit" system of pulverized-fuel firing, in which each boiler has a separate self-contained pulverizer, separators and feeders in one machine, because in the first place this is more applicable to smaller boiler plants and not so much to large power station work, and secondly, authentic data as to prolonged performance do not appear to be available. Similarly he has not discussed the various different systems of pulverized fuel on the so-called "central" system (preparing the coal at some central position and supplying the different burners) because he feels that a better consideration will be obtained by

confining attention to what is actually being accomplished on certain large power-station boiler plants.

The paper gives first of all a sketch of the early history of pulverized fuel, followed by a brief account of the position to-day in the United States with regard to the use of pulverized fuel for steam generation. Since the whole position in this respect has been changed by the starting up of the Lakeside station in December 1920, the author has considered in some detail, after a brief mention of the general principles of pulverized-fuel firing, the general opinions of the relative advantages and disadvantages of pulverized fuel for steam generation held prior to 1920. Following this a detailed description of the actual plant at Lakeside, in addition to the mention of several other plants, is a convenient method of discussing the modern principles of pulverized fuel which have led to such an enormous development during the last three years.

The greater part of the paper is then taken up with a consideration, step by step, of the actual results obtained at Lakeside, and in a number of cases also on other large pulverized-fuel plants, as compared with modern mechanical-stoker practice, Dalmarnock power station, Glasgow, being taken as typical of the best class of British station. Such a consideration, of course, covers a very wide field, but the author trusts that the importance of the subject will be considered ample justification.

The History of Pulverized Fuel.

The idea of using coal in a finely pulverized condition for combustion as fuel, and also in carbonization and total gasification processes, is of very ancient origin. Pulverized coal was apparently first experimented with somewhere about 1820, but the work was kept secret and the results obtained are not known.

One of the earliest patents on the subject was that of J. D. Whelpley and J. J. Storer, both of Boston, Mass., U.S.A., whose British patent is 1471/1866, in which essentially pulverized coal was to be used by being fed into and over furnaces as an aid to hand-firing. The patent is entitled: "A novel application of fuel and of the fluxes or reducing agents used in metallurgic processes and consists in employing fuel and fluxes in a finely divided state and feeding them into the air blast of a furnace or fire box so that they may be floated on the blast during their consumption and thus generate their heat and perform their reactions at the working point by this means, giving great economy, more perfect results and better control over the operation in which the fuel is employed. The invention is equally applicable to furnaces for metallurgic operations and to fire boxes where the auxiliary blast is used."

Whelpley and Storer thoroughly understood the importance of the intimate contact of the fuel and the air, or the ore and the reducing agent, as obtained by pulverizing, and they used for the supply of pulverized fuel or other material a fan-blower arrangement, consisting essentially of a revolving cylindrical brush to supply both the fuel and the air at the same time. The process was intended to apply more to the reduction of ores, but pulverized-coal burning is also very specifically mentioned, although a later patent (1493/1866) relates to the use of pulverized ores only.

The first man, however, to investigate thoroughly the whole question of pulverized fuel from many aspects would appear to have been T. R. Crampton, of Westminster. Crampton took out a considerable number of patents on a great variety of subjects, such as special roadways and the construction of forts, and his first pulverized-fuel patent, a very long one, is 2539/1868. A portion of this patent covers the process of grinding coal in ordinary millstones but using a blast of air between the stones to remove the finely ground material as it is formed, whilst at the same time keeping the stones cool, and secondly, using the same fan to discharge into the furnace the pulverized coal mixed with air. The patent also includes the idea of burning a mixture of pulverized coal and air by passing them in a zigzag course between the extended surfaces of a heated firebrick furnace chamber, so as to aid the combustion, while another idea was to use in the bottom of the combustion chamber molten iron, molten slag or other molten material further to aid the combustion.

Crampton then took out another very voluminous patent (3504/1869) on pulverized-coal burning, consisting chiefly of numerous modifications of his previous patent 2539/1868, but especially from the point of view of causing different streams of pulverized coal and air to mix so as to ensure better combustion. The degree of grinding used was not very fine, the powder passing through a 30-mesh screen (30 holes per linear inch = 900 holes per square inch) for ordinary bituminous coal, but for anthracite or coke he suggested 40–80 mesh screens, and he also used in the most ingenious manner the principle of regenerating the heat, supplying for combustion air heated by coils in the hot exit gases.

Further remarkable ideas contained in Crampton's patents included a special bridge wall sloping in such a manner as to reflect the streams of air and burning fuel at an angle in order to secure still better mixing, and a highly ingenious arrangement of equal coal feed across the width of the furnace by means of air, including primary air to convey and mix with the coal and secondary air to complete the combustion. Various later patents of Crampton's in connection with the burning of pulverized coal were 2606/1870 and 931/1871, chiefly in connection with various special furnaces.

Crampton also took out a patent in 1872 for the continuous carbonization of coal in a pulverized condition, by grinding the coal to a fineness of all through a 30-mesh screen and allowing it to fall continuously down a very high vertical cylinder, the outside centre portion of which was heated by a gas-fired, encircling combustion chamber, so that the coal was carbonized almost instantaneously, the coke, in a fine powder, accumulating at the bottom and the gaseous and volatile products escaping at the top. Here again the details of the continuous coal feeder, the method of distributing the coal evenly throughout the fall, and the automatic removal of the coke dust "in step" with the admission of the coal, are all on the most ingenious principles. This idea of the carbonization

of pulverized coal has been allowed to lie dormant for over half a century and is only now occupying serious attention for low-temperature carbonization. It is evident that Crampton possessed an astonishing grasp of the whole of the principles and possibilities of pulverized fuel burning as applied not only to steam generation but also in connection with many types of furnace, especially such as are used in the glass and steel industries.

In spite, however, of this remarkable pioneer work and many other patents which followed, pulverized fuel made no headway at all, chiefly because the necessity of drying the coal was not realized, but also owing to the lack of modern types of grinding and pulverizing machinery, to the fact that the fuel was not pulverized to a sufficient extent, and to the difficulty of controlling the flame. The first commercial application of pulverized fuel was in the cement industry, and it is stated to have been used originally in this connection in Great Britain in 1884, although the evidence in support of this is not conclusive. In the United States, which may justly be stated to be the home of pulverized fuel, the first large-scale application in the cement industry was in 1894, when Hurry and Seaman used it at the works of the Atlas Portland Cement Co.

Shortly after this time pulverized fuel began to be used regularly in America for the manufacture of cement, and to-day approximately 90 per cent of the cement output of the United States is produced with the aid of such fuel. Also various other industries, especially in connection with iron, steel and glass, have adopted this method of firing for furnace work, and at the present time altogether probably over 30 000 000 tons of pulverized coal per annum are being used in America. As far as the British cement industry is concerned, the first rotary kiln with pulverized fuel seems to have been started up in 1901 at Swanscombe, and to-day also over 90 per cent of British cement is made with pulverized fuel.

With regard to steam generation, with which this paper is most directly concerned, pulverized fuel had made remarkably slow progress until a few years ago. It was first experimented with seriously for locomotive firing in about 1900 by the Manhattan Elevated Railroad in the United States, but the experiments were abandoned. Since then, however, various American railways have investigated the subject, several of them on quite a large scale. The work was stopped by the war but has since been resumed, and, as is well known, extensive developments in the application of pulverized-fuel firing to locomotives are now taking place in Brazil.

In stationary, land boiler plants the same slow progress obtained. Naturally, the use of pulverized coal in the cement industry led various cement works to experiment with this method of firing on their own boilers, and in 1901, for example, the Alpha Portland Co., and in 1902 the Lehigh Portland Cement Co., tried pulverized coal on water-tube boilers. The efficiencies obtained were generally extremely good, but for some reason or other, whether practical difficulties or merely lack of interest, the work was not followed up and practically nothing was done in the cement industry in the United States to use pulverized coal for steam generation until 1917 or 1918, when the Ashgrove Lime and Cement Co. adopted it on Heine water-tube boilers. Altogether there was little real application of pulverized fuel to steam generation in the United States before about 1913.

In Great Britain the principle has made practically no headway at all. It is believed that the British Admiralty have experimented with it, and for some years a few Bettington vertical boilers, fired with pulverized coal, were in operation. Even to-day there is, so far as the author is aware, only one large boiler plant in Great Britain—at Hammersmith electricity supply station—running on pulverized fuel, and he understands that 3 boilers, evaporating approximately 45 000 lb. of water per hour, are now in operation with very satisfactory results. There is also the new installation at Peterborough of "unit" pulverizers on two medium-sized boilers (25 000 lb. evaporation), and one or two small boilers have been equipped for experimental purposes, whilst general furnace work is also disappointing.

In the United States a fair amount of progress was made between, say, 1914 and 1920 with pulverized coal for steam generation on moderate-sized industrial plants. Thus some of the earliest American boiler plants to adopt pulverized fuel were the M.K. and T. Railroad boiler plant of a total of 84 250 h p. (American) at Parsons, Kansas; the Puget Sound Electric Light, Heat and Power Co. at the Western Avenue station with a 4 100-h.p. (American) installation; the American Locomotive Co. at Schenectady; the Sizer Forge Co. of Buffalo; the Susquehanna Collieries; and the Atlantic Steel Co.

Previous to 1918, as already stated, these plants were moderate-sized industrial installations and did not include any power stations. A list of prominent installations equipped from 1916 to 1918 showed boilers varying from 100 to 600 h.p. (American) mostly in plants of 1–10 boilers. The results obtained on some of these plants were very good, especially as regards efficiency.

Many engineers had also pointed out the advantages of pulverized coal, for example F. A. Scheffler and H. C. Barnhurst in their paper on "Pulverized Coal for Stationary Boilers," read in June 1919 before the American Society of Mechanical Engineers, but still the principle made slow progress, chiefly because of the difficulty of solving the problem of the maintenance of the furnaces. Much the same state of affairs existed in France and Germany, where a limited number of plants were at work.

The position as regards steam generation was, however, entirely altered by the final perfection of the Lopulco system of pulverized fuel and its successful adoption on a very large power-station plant, the Lakeside station of the Milwaukee Electric Railway and Power Co., the first section of 40 000 kW of which was started up in December 1920.

The remarkable success of the installation has quickly effected a revolution in the position of pulverized fuel for steam generation, and to-day, in the short space of three years, some of the largest and most noted power stations in the world have adopted it.

The Present Position of Steam Generation by Means of Pulverized Fuel.

The majority of power station engineers in Great Britain do not perhaps realize the extent of the application of pulverized fuel to steam generation in the United States, especially to power station work. In many cases, for example, the impression would appear to be that pulverized fuel is merely a fad, and in any case a matter for cautious experimenting for months on end with one boiler at a time, to test it and find out its faults. For this reason, therefore, a few facts as to the real situation will not be out of place.

The boiler-plant installations in America, in addition to Lakeside, now running on Lopulco pulverized fuel include the West Pennsylvania Power Co. of Springdale, Pa.; the St. Joseph Lead Co., Rivermines, Mo.; the Lima Locomotive Co., Ohio; and the Allegheny Steel Co. of Breckenridge, Pa. Also, the well-known River Rouge plant of the Ford Motor Co. at Detroit has boilers of 26 470 sq. ft. heating surface, fired with mixed pulverized coal and blast-furnace gas, having a normal evaporation of about 220 000 lb. of water per hour from and at 212° F. with 275 000 lb. reasonable overload.

About the middle of this year (1923) the number of large boiler plants in operation in America on the Lopulco system was nine, comprising 43 boilers with a total heating surface of approximately 360 000 sq. ft. Probably about 300 000 sq. ft. of this is in operation at one time, which at the very moderate figure (low-capacity plant) of 0·75 lb. of coal burnt per sq. ft. of heating surface per hour (6·50 lb. of water evaporated) corresponds to, say, 120·5 tons per hour or something like 850 000–1 000 000 tons per annum, equal to, say, 47 standard 50 000-lb. boilers in constant operation. Probably over 2 000 000 tons of pulverized coal have so far been burnt on the Lopulco system.

The position in this respect will, however, be entirely altered almost within the next few months. At the present time (October 1923) 29 different plants are being equipped. In addition to the doubling of the River Rouge plant (four more boilers each of 26 470 sq. ft. heating surface being added), the Ford plant in Canada is in the course of conversion; the Lakeside station is also being doubled (8 more boilers each of 17 500 sq. ft. being added); the first section of 8 boilers of 17 800 sq. ft. each are being erected for the Union Electric Co.'s new Cahokia power station for St. Louis (to be eventually 300 000 kW); the Cleveland Electric Co. are installing 4 boilers each of 30 600 sq. ft. heating surface (the largest boilers in the world, with a normal evaporation of 300 000 lb. per hour); the Union d'Électricité are equipping 4 boilers each of 16 678 sq. ft. heating surface at Vitry (Paris); and the United Electric Railways plant at Rhode Island is also being fitted with 3 boilers each of 12 600 sq. ft., whilst most recently the Duquesne Light Co. are installing five 26 500-sq. ft. boilers at their Colfax station, and the Detroit Edison Co. six 29 500-sq. ft. boilers at the New Trenton Channel station.

The total boiler heating-surface of these 29 boiler plants (comprising 91 boilers) now being equipped with Lopulco pulverized fuel is approximately 1 400 000 sq. ft., corresponding to a coal bill—calculated as before—of about 385 tons per hour, or approximately 2 695 000 tons of coal per annum, equal to, say, 142 standard 50 000-lb. boilers in constant operation. This will make a total of 3 400 000 tons of pulverized coal per annum, or nearly half the power-station capacity of the whole of the United Kingdom.

It will be agreed, therefore, that whatever may be the advantages and disadvantages of pulverized fuel for steam generation, it has long since passed the experimental stage, and what may be termed all the main problems and difficulties have already been solved in America. Obviously the simplest method, therefore, for a British power station engineer is not to experiment himself, but to save time by visiting the United States and inspecting the position on the spot so as to take advantage of all the accumulated experience that is to be had for the asking.

The General Principles of Pulverized Fuel.

The general principles of pulverized-fuel practice are already fairly well known, so that it will only be necessary to give the briefest outline of them.

The coal is first crushed and then passed over a magnetic separator to get rid of any accidental particles of iron which would cause damage to the pulverizers. The crushed coal is then dried, first of all to enable the pulverizers to work efficiently, but also because the pulverized fuel in a very dry state is perfectly "fluid," and the ease with which the material may be conveyed, controlled, and mixed with air is increased, whilst the speed and temperature of ignition of the pulverized material are greatly increased. The degree of drying is a matter of opinion and will be discussed later in the paper, but the modern practice with pulverized fuel is to dry it so that it contains not more than 2 per cent of moisture, and preferably 1–2 per cent. The "unit" system of pulverizing, however, is stated to handle undried coal so long as the moisture content does not exceed 10 per cent.

In general, damp coal "packs" in the pulverizer and greatly increases the horse-power required, whilst reducing the output. Thus, in an example mentioned by Mr. Cecil F. Herrington of a pulverized-coal plant of the Bethlehem Steel Co. of a capacity of 135 tons of coal per 24 hours, the coal contained 5 per cent of moisture, but if used in this condition the output of the pulverizers was reduced 20 per cent as compared with dried coal with 1–2 per cent of moisture. Dried coal also has the advantage that it is less liable to spontaneous combustion and there is no tendency to stick in the conveying pipes or pulverized-fuel bunkers, so that drying to less than 2 per cent of moisture is altogether a paying proposition.

The dried coal is then pulverized in ball mills, and here again the exact degree of treatment to which the coal is subjected is a matter of opinion. To-day, however, rough average practice as regards the fineness of the material is that about 90 per cent of an average sample must pass through a 100-mesh screen (100 holes to the linear inch, 10 000 holes per sq. in.) and 65 per cent through a 200-mesh screen, but much depends on the quality of the coal. Excessively fine

grinding, however, such as 85 per cent through a 200-mesh screen, is not now as a rule necessary under modern conditions.* The pulverized coal is then mixed with a certain amount of air and burnt in burners. These are of three general types which may be defined roughly as follows :—

(1) Natural-draught burners, in which the pulverized coal is taken into the furnace by this means only.
(2) Mechanical coal-feed burners, using revolving fans or brushes.
(3) Compressed-air burners, using air under pressure to blow the fuel into the furnace.

The modern burner is also so arranged that the air is only mixed in any quantity with the pulverized fuel very near to the burner itself, partly because the mixture is explosive, and also so as not to cause any separation of the heavier fuel from the air and give a mixture of uneven strata for combustion, as would be the case if the mixed fuel and air had to travel a long distance. A good type of burner gives less than 3 per cent variation in the air-fuel mixture at any portion of the travel.

Advantages (up to 1920) of Pulverized Fuel for Steam Generation.

As already stated, the position with regard to pulverized fuel has entirely changed since 1920, from which date the experience gained by the burning of several million tons of pulverized coal, mostly in large plants and under the latest conditions, has considerably altered many of our previous ideas on the subject. The general opinions up to 1920 in Great Britain as to the advantages and disadvantages of pulverized fuel as compared with mechanical stoking, some of which contradict one another, can be summarized as follows, and it may be stated also that Great Britain has not been very well informed on the matter during the past few years.

(1) *High boiler-plant efficiency.*—It has long been admitted that pulverized fuel, from the point of view of efficiency of steam generation, gives results far superior to any method using coal in the ordinary way, whether crushed or in the lump condition, and with either hand or mechanical firing. The chief reason for this was known to be the extremely intimate mixture of the air and the finely divided fuel, so that a very much reduced amount of excess air over the theoretical is required. It was contended by some advocates of pulverized fuel that the figure for excess air was only about 20 per cent above that required by theoretical conditions, as compared with 50 per cent for very good plants with mechanical stoking. Consequently, fuel in a pulverized condition burns smokelessly with about 17–18 per cent of CO_2, no CO, and such an intense heat, with maximum radiation, that one of the problems has long been to get the brickwork to withstand it. In a general way it was stated also that 82½–85 per cent boiler-plant efficiency was to be obtained, with a saving of 20–25 per cent in the coal bill as compared with mechanical stoking, always provided that various other difficulties could be surmounted. As examples of individual opinions, Mr. N. C. Harrison of the Atlantic Steel Co. stated that the boiler-plant efficiency obtained was 85·22 per cent with a very large plant of 100 tons of coal per 24 hours, as against 78·04 per cent for mechanical stokers, without deducting the auxiliary power used in either case, and Scheffler and Barnhurst, in their paper read in 1919 before the American Society of Mechanical Engineers, gave a list of 18 ordinary industrial boiler plants fired with pulverized coal, in which the efficiency obtained varied from 72·7 to 85 per cent.

(2) *Complete combustion in the ash.*—One of the reasons of the greater efficiency was also the universally recognized fact that pulverized fuel gives complete combustion, as proved by the very fine ash resulting, whereas with practically every form of mechanical stoking there is a loss due to unburnt and partially burnt fuel in the comparatively large masses of ash and clinker and to the riddlings, i.e. fuel falling between the portions of the furnace.

(3) *Absence of moisture in the coal when burnt.*—The fact that pulverized coal was burnt with only about 1 per cent of moisture, and certainly not over 2 per cent, was also agreed to be an advantage, since the temperature of the flame is not reduced, by having to evaporate a comparatively large volume of water in the fuel.

(4) *Ease and convenience of transport in the boiler house.*—Pulverized fuel has semi-liquid properties and can be blown with the greatest ease for great distances through small-bore pipes bent round corners in almost any fashion.

(5) *Great flexibility as regards the variety of coal that can be burnt.*—It was also generally agreed that pulverized-coal firing is much more flexible as regards the variety of coal that can be burnt. For example, the principle of grinding the coal extremely fine obviated clinkering difficulties, so that coals with a high ash or sulphur content could be burnt efficiently, whereas it was almost impossible to consume them in many types of mechanical stoker. The advantages in this direction were certainly not realized to the full extent, especially in the case of a very large power station in which there is almost always quite a considerable variation in the quality of the coals used, often within a few hours. Finally, an important advantage recognized was that pulverized fuel works perfectly in conjunction with oil fuel and any gaseous fuel such as blast-furnace gas or coke-oven gas.

(6) *Greater flexibility in steam output.*—Another advantage claimed was greatly increased flexibility of the steam output of the plant, it being possible to take an enormous overload, often as much as 100 per cent in an emergency, whilst the firing could be started up or shut down in a remarkably short space of time. Another very important point is that, in contra-distinction to the case of mechanical stoking, these fluctuations result in comparatively little difference in efficiency.

(7) *Reduced stand-by and banking losses.*—In consequence of this greater flexibility in steam output,

* This point is dealt with in detail in a paper (No. 1780) entitled "Boiler Tests with Pulverized Coal," by H. Kreisinger and J. Blizard, read at the Spring Meeting of the American Society of Mechanical Engineers, Chicago, 21–26 May, 1921.

banking and stand-by losses, a serious item in many mechanically-fired plants with erratic steam demand, are automatically eliminated to a very great extent.

(8) *Much greater ease of scientific control.*—It was regarded as a minor advantage of pulverized fuel that it lent itself to a much more efficient control of the working of the plant, since a current of air and pulverized fuel through pipes is obviously much more simple to adjust, control and measure than is the fuel in the case of mechanical stoking. The real advantages in this direction were, however, hardly realized.

(9) *Reduced labour costs.*—Another advantage generally claimed was a net saving in labour as compared with mechanical stoking, although in the majority of cases this does not seem to have been based on any very conclusive data. Mr. N. C. Harrison, however, in the case of the Atlantic Steel Co. already mentioned, gave the pre-war labour costs, at the rate of $0·365 per hour, as approximately $0·195 per ton at 90 tons per 24 hours, or $0·176 at the full output per 24 hours—a very low rate.

Disadvantages (up to 1920) of Pulverized Fuel for Steam Generation.

It may be stated in the first place that the disadvantages given are in some instances exaggerated, and were in many cases due to defective plant and lack of knowledge.

(1) *Power consumption in the preparation of the fuel.*—It was considered that one of the chief disadvantages of pulverized fuel was the excessive cost of preparing the fuel, that is in handling, crushing, drying and pulverizing, particularly the power required by the pulverizers. Great differences of opinion, however, existed on this point. For example, R. Trautschold in 1917, for a 50-ton plant per 24 hours, with coal at $3 per ton, stated that the figure was 43 per cent of the cost of the coal, including 13·25 per cent for equipment, 5·75 per cent for drying, 20 per cent for pulverizing, and 4 per cent for conveying.

Some figures in Mr. L. C. Harvey's report in 1918 gave for this particular year a total average cost of pulverizing per ton for a 50-ton plant per 24 hours of $0·58 (2s. 5d.), for a 100-ton plant $0·51 (2s. 1½d.), for a 150-ton plant $0·48 (2s.), and for a 200-ton plant $0·45 (1s. 10½d.). These figures do not include interest and depreciation or the cost of conveying the coal to the furnaces, and have been converted to English rates of wages, 10d. to 1s. 3d. per hour, being based also on coal containing 7 per cent of moisture at $5 (£1 0s. 10d.) per ton delivered, 6 lb. evaporation per lb. of coal burned, repairs at 7 cents per ton, and power 12·7 cents (6·35d.) per ton pulverized. The figure of " 6 lb. evaporation " is, however, presumably a misprint.

In the same report are given, however, some specimen examples of plants with American prices, including interest and depreciation during the 1918 period (when prices were high), as follows: A plant of 80 tons per day in which the total cost of pulverizing was $2·21 (9s. 2½d.) per ton, the cost of another similar plant being $2·34 (9s. 9d.), whilst a plant of 30 tons averaged $1·489 (6s. 2·45d.) per ton, and a large 150-ton plant $0·772 (3s. 2½d.) per ton. It is also stated in the report that the average cost of drying the coal was equivalent to the cost of 20–30 lb. of coal per ton, or 0·90–1·30 per cent of the amount dried under average conditions, the final exit temperature of the coal being not over 250° F.

Mr. Harrison, in regard to the plant already mentioned as giving 85·22 per cent efficiency with pulverized coal, states that the total cost of preparation of the fuel was equivalent to 6 per cent of the cost of coal consumed.

Obviously the amount of moisture in the coal, which may be anything from 1 to 20 per cent, and the size of the installation play an important part, but in general it was maintained that this figure of the cost of preparation of the fuel from the lump coal to the burners, and including the cost of the fine ash disposal, was far greater than that of mechanical stoking, the crushing and handling of the coal, the driving of the stoker, the mechanical draught and the working of the mechanical ash conveyers.

(2) *Cost of wear and tear and breakdowns.*—Another disadvantage regarded by many engineers as inherent in pulverized fuel, although usually on scanty grounds as regards actual data and experience, was excessive wear and tear on the preparation plant generally, together with risk of breakdowns, not only in the pulverizers but also in the pipe circuits and at the burners. It was a general opinion that coal could not be pulverized continuously in huge quantities without incurring an extensive repair bill, and the wear and tear and the risk of breakdowns were regarded as being far in excess of those obtaining with mechanical stokers, even including the mechanical handling and (if necessary) crushing of the ash and clinker.

As a typical individual opinion, N. C. Harrison gives the total cost of repairs on the Atlantic City steel plant, dealing with 100 tons per day, as $1 002·47 for 2 months' running, 5 275 tons of coal being pulverized, corresponding to $0·190 per ton.

(3) *Deterioration of the furnace linings.*—Another of the chief objections to pulverized fuel was stated to be the excessive wear and tear and deterioration of the firebrick linings as compared with those in the case of mechanical stoking, due to the intense heat of the combustion, so that in many cases it was impossible to work the burners at their maximum efficiency, i.e. 17 to 18 per cent of CO_2, because the brickwork would not withstand the conditions, although obviously the higher the temperature the more efficient was the combustion. A minor defect in this connection was also stated to be the sand-blast action of the fine hot ash on the brickwork.

(4) *Damage to the boiler.*—Some engineers also claimed that pulverized-fuel firing was apt to cause damage to the boiler because of what they regarded as intense local heat.

(5) *Dusty and dirty nature of the operations.*—A common idea was that the pulverizing of dry coal was an extremely dirty, dusty and objectionable job, whilst it was impossible to keep the boiler plant in a clean condition.

(6) *Absence of proper temperature control.*—In spite of the general agreement as to the ease of control in the

working of pulverized fuel, a number of engineers were of the opinion that another disadvantage of such fuel was the lack of proper methods of controlling the temperature of the flame, so that the amount of coal burnt could not easily be adjusted to suit fluctuating evaporations. This undoubtedly was the case in one or two systems of pulverized-fuel firing.

(7) *Danger of explosions.*—A very common objection to pulverized coal was the fact that it was regarded as being much more dangerous than the ordinary methods of firing, especially from the point of view of greatly increased liability to serious explosions. Coal in an extremely fine state of division, particularly if the volatile content is high, is a very explosive material, as we know for example from the historical coal-dust explosion experiments inaugurated by the late Sir William Garforth at Altofts Collieries and since carried on by the Government at Eskmeals.

(8) *Danger of spontaneous combustion.*—In this connection an analogous disadvantage of pulverized fuel was the greatly increased liability of the coal to spontaneous combustion, especially when containing over 1 per cent of moisture. For these reasons special precautions had to be taken to keep down the temperature and prevent re-absorption of moisture, whilst not more than 5 to 6 ft. depth of coal was allowed in the bunkers. On this account also, generally not more than 10–15 hours' supply is stored at any one time, and the period of storage in any case should not exceed three days, whilst the bunkers have to be designed so that the material cannot accumulate in the corners. Further, when fires do start they are extremely difficult to put out and flooding has to be resorted to.

(9) *Ash troubles.*—Another series of objections to pulverized fuel centred round the ash, which is of course in an extremely fine state of division. In the first place it was stated that much of this fine ash, at least 50–75 per cent of the total ash in the coal, was discharged from the top of the chimney, causing a nuisance in the neighbourhood. Secondly, the ash becomes molten because of the intense heat, and is blown all over the inside of the boiler plant, not only on the boiler tubes and the superheater, but also in the economizer tubes and flues. Another serious difficulty that was not generally realized until large installations were set to work, was "slagging." That is to say, the large amount of ash accumulating at the bottom of the furnace chambers becomes molten and forms an incandescent, sticky mass, which corrodes and "fluxes" the brickwork. It is also very difficult to handle, particularly as the viscosity varies with the quality of the coal. Slagging was found to be particularly objectionable in the case of low-grade coals, such as Illinois and Indiana qualities, high in sulphur, with a low-melting-point ash, and the difficulty is accentuated at high rating.

(10) *Capital costs.*—Naturally it is in any case difficult to give data on this point, but, whether justifiably or not, the capital cost of a pulverized-coal installation was regarded as being considerably higher than that of mechanical stoking for the same net duty, which was said to be partially due to the fact that it was necessary for nearly all the pulverized-fuel plant required to be in duplicate because of the liability to breakdowns. Further, the space required by the preparation equipment was thought to be excessive, necessitating increased cost in land and buildings.

In the United States the pre-war cost of a 100-ton-per-24-hour pulverized-coal plant (5 000 kW) was stated to be very roughly about \$45 000 to \$50 000, although F. A. Scheffler and H. O. Barnhurst in their publications take the cost of a 100-ton plant (5 000 kW) as \$64 000, or \$12·80 per kW, and of a 1 000-ton plant as \$240 000, or \$4·80 per kW.

Mr. L. C. Harvey in his report of 1918 gives the cost of typical pulverized-coal plants complete (including buildings), calculated on the basis of British conditions in 1918 (when prices were high), as follows:—

Tons per day	Cost of plant	
	\$	£
10	46 500	9 687
50	55 500	11 562
100	67 500	14 062
150	75 000	15 625
200	93 000	19 375
250	93 000	19 375

TABLE 1.

Figures given by N. C. Harrison in regard to the Atlantic Steel plant.

	Costs per ton at outputs per day of		
	80 tons	90 tons	100 tons
	\$	\$	\$
Labour at \$0·365 per hour	0·2200	0·1950	0·1760
Repairs	0·1900	0·1900	0·1900
Power for handling, crushing and pulverizing	0·1340	0·1340	0·1340
Drying 2·62 per cent moisture coal at \$5.0 per ton (0·40 per cent)	0·0218	0·0218	0·0218
Total cost per ton	0·5658	0·5408	0·5218

In the United States it has been customary for the past few years to take for depreciation in connection with pulverized fuel, a life of 40 years for the buildings, 15 years for the old-fashioned rotary driers, and 20 years for the rest of the plant. Thus on a 100-ton-per-24-hour plant the depreciation figure is 12 cents net per ton, which seems a small amount. Taxes and insurance were regarded as constituting 2 per cent of the total capital expenditure.

(11) *Total costs of preparation.*—Finally, as regards the total inclusive costs of pulverized fuel, some makers of the plant in America are said to have estimated this as $0·35 per ton, although exactly what this includes is not clear.

Figures given by N. C. Harrison in regard to the Atlantic Steel plant are given in Table 1. Taking the average figure as $0·54 per ton, this corresponds to about 11 per cent of the coal burnt, excluding capital charges.

F. A. Scheffler and H. O. Barnhurst give the total cost per ton of coal handled as $0·3975 per ton at 100 tons per 24 hours, and $0·2975 per ton at 1 000 tons in 24 hours, and they estimate the total costs as $0·6575 and $0·3895 per ton including interest on capital, rates and taxes, and depreciation, taking the capital cost of the two plants as $64 000 and $240 000, as already stated.

The Lakeside Plant of the Milwaukee Electric Railway and Light Co.

Before describing this installation, it will be as well to state in a few words the essentials of the Lopulco system of pulverized fuel. These include the use of the water screen, an arrangement of steel tubes in the bottom of the furnace chamber, which has done more than anything else to solve the practical problems of very large-scale pulverized-fuel burning, and through which the boiler water circulates so as to cool the accumulated ash and prevent slagging, combined with hollow furnace walls. The latter are kept cool by a current of cold air, and the heated air is then passed as secondary air to the burners, which are of the air-pressure design, with a special type of automatic coal feeder, and on the "triplex" principle, the flame being directed downwards into a very large combustion chamber. Finally the latest type of drier, invented since the Lakeside installation, is of a simple vertical design through which the coal passes continuously by gravity, being dried by the waste hot gases in the chimney base, no coal at all being required.

In 1915 the Milwaukee Electric Railway and Light Co. found it necessary to make extensive additions to their power plant and finally planned a new 200 000-kW station, the site for which was purchased in 1916 at Lakeside, 1 mile south of the southern limits of the city of Milwaukee, with 6 000 feet frontage on Lake Michigan. It was decided to equip this huge plant entirely with the Lopulco system of pulverized fuel, because of the very satisfactory experience with this system at the old power station of the company at Oneida-street, Michigan. This latter plant, which is still running, consists of 5 Edgemoor water-tube boilers each of 468 (nominal) American horse-power, and, on the advice of the chief engineer of the company (Mr. Anderson), was equipped with pulverized-coal firing in 1918, after previous tests on one boiler. The result was a great success, although the plant was not built for pulverized fuel and the working of the system was handicapped in various ways, for instance by the absence of economizers.

A very extensive series of tests, each of 17–25 hours' duration and spread over 10 months, was carried out by Mr. Anderson and also by Mr. H. Kreisinger, then of the United States Bureau of Mines, to determine the performance of pulverized Illinois and other low-quality coal under every possible condition, but particularly as regards the fineness of grinding necessary and absence of moisture required for the most efficient working. The net result of the many months' running and almost continual testing on the Oneida-street plant was to show that with the inferior Illinois coal results of 80·20–82·70 per cent efficiency were obtained on long tests with boiler and superheater only, and the average efficiency from month to month was 80 per cent and over.* It was also discovered, as a result of this experience, that it is not necessary to pulverize the coal as finely as was previously thought, the average figure to-day being—as already stated—equivalent to about 90 per cent through a 100-mesh screen and 65 per cent through a 200-mesh screen. What is really required is *uniform* grinding, i.e. not so much 85 per cent through a 200 mesh and a residue of large particles, but, if possible, 100 per cent through a 100 mesh, when 65 per cent through a 200 mesh is ample as a rule. Further, it was early discovered that it was not essential to dry the coal down to 1 per cent of moisture or less, and that in most cases 2 per cent was quite satisfactory, provided the drying was even.

Because of difficulties due to the war, a start was not made with the Lakeside plant until December 1919, but the whole of the present installation was completed and running in December 1920, with a duty of 40 000 kW (50 000 kW at full output), together with much of the buildings, foundations and cooling-water plant for 200 000 kW, whilst at the present time a further 40 000 kW is being installed. The whole plant was designed entirely by Mr. Anderson and the engineering staff of the Milwaukee Electric Railway and Light Co., the Combustion Engineering Co. being responsible for the pulverized-coal section of the plant.

The complete installation is divided into four main parts, the switch-house, the turbine room, the boiler house, and the pulverizing section, the latter being 108 ft. by 125 ft. and at present equipped for pulverizing coal for 80 000 kW. As giving some idea of the size of this station, the full 200 000-kW plant will require 360 000 gallons of cooling water a minute, or 518 000 000 gallons per 24 hours, which will be obtained from the adjoining Lake Michigan.

The present boiler plant for 40 000 kW consists of eight 1 306-h.p. (American) Edgemoor four-pass water-tube boilers, working at 300 lb. pressure and arranged in two sections of four each, one section (with one boiler as a stand-by) supplying one 20 000-kW turbo-generator.

* See also H. D. Savage: "The Use of Powdered Coal under Steam Boilers." Paper read in New York before the American Iron and Steel Institute, 27th May, 1921.

For the full output of 200 000 kW, or 160 000 kW normal running, there will thus be 24 of these boilers, all fired with pulverized fuel.

The principal dimensions of each boiler, normally evaporating 90 000 lb. from and at 212° F. per hour and 115 000 lb. overload, are as follows :—

Number of tubes high	15
Number of tubes wide	38 and 37
Total number of tubes	563
Length of tubes	20 feet
Diameter of tubes	4 inches
Number of steam drums	5
Total heating surface of boiler	13 060 sq. ft.

The boilers are fitted with Foster superheaters of such a capacity as to heat 90 000 lb. of steam per hour from 411° F. (300 lb. pressure) to a superheat of 200 degrees F., i.e. a temperature of about 611° F. Each boiler is also fitted with a Sturtevant cast-iron economizer installation of 7 603 sq. ft. heating surface, with by-pass connection to the chimney, the feed water entering the economizers at 140° F. and leaving at 253° F., i.e. being raised through 113 degrees F. and saving about 10 per cent in the coal bill. The principal dimensions of the economizer installation are as follows :—

Number of tubes wide	12
Number of tubes long	44
Total number of tubes	528
Length of tubes	12 feet
Outside diameter of tubes ..	4½ inches

It is interesting to note that this very modern high-pressure American boiler plant retains the use of the cast-iron economizer. In the author's opinion, the tendency in power station design, especially in Great Britain, to use steel-tube economizers for over 200 lb. pressure is a fundamental mistake. Steel will not withstand for long the corrosive action of the flue gases, and the author is convinced that the resulting excessive wear and tear, breakdowns, and stoppage for replacements are not worth the slight advantages of the steel-tube economizer as regards lightness, convenience, and the somewhat less space occupied, especially since cast-iron economizers can be arranged to work at any given boiler pressure by installing an extra turbine feed pump between the economizer and the boiler.

The plant is fitted with a steam-turbine-driven induced-draught fan for each boiler, discharging into concrete flues 8 ft. 0 in. high and 11 ft. 6 in. to 18 ft. 0 in. wide, leading to two reinforced concrete chimneys 220 ft. high, the diameter at the bottom being 16 ft. 6 in. and at the top 15 ft. 0 in., the main shell being 5 in. thick at the top and 24 in. thick at the bottom, and having also a 4-in. concrete lining for a height of 60 ft.

As regards boiler feed-pumps, the maximum evaporation of the 8-boiler installation is approximately 920 000 lb. per hour, the normal figure being, as already stated, 90 000 lb. per boiler with 6 boilers in operation.

The feed pumps consist of two 6-in centrifugal pumps, driven by 250-h.p. steam turbines and each delivering 39 000 gallons per hour, and two 4-in. centrifugal pumps driven by 150-h.p. motors and delivering 24 000 gallons per hour, so that there is the ample reserve of one steam-driven pump or two motor-driven pumps. The condenser water (at about 80° F.) from the turbine condensers is pumped to an overhead hot-well tank, and falls by gravity through two feed-water heaters, which raise its temperature to approximately 140° F. It then passes through a Lea V-notch feed-water meter of 800 000 lb. per hour capacity, situated above the feed pumps, giving a 15-ft. suction head. It may be stated that the whole plant is so arranged that part of the auxiliaries, e.g. boiler feed-pumps, induced-draught fans, circulating pumps, etc., are steam-driven, the exhaust steam being used to heat the feed water so that it enters the economizers at a temperature well over 100° F. At the same time no latent heat is lost, the balance of the steam required being provided by the house turbine.

The railway coal-cars as they enter the plant are dumped by means of a Robins-Scherzer rotary car dumper, and dropped into a track hopper with bottom shaker feeders, fitted by the Robins Belt Co. Belt conveyers (36-in.), with a total capacity of 250 tons per hour at a speed of 250 ft. per min., then convey the coal over a magnetic separator to remove any iron particles, and pass it through a two-roller crusher and hammer mill, where it is crushed to a size, say, all through a ¾-in. mesh, the capacity of this crushing plant being 150 tons of mine coal per hour. The crushed coal is then conveyed by another installation of three belt conveyers to overhead green-coal bunkers in the pulverizing-plant building, each belt having a travelling trip arrangement to enable the coal to be discharged at any point as required. This green-coal bunker has a storage capacity of 3 400 tons, that is, 3½ days' supply for maximum duty on all boilers, and the crushed coal is taken from here by means of three screw conveyers over automatic weighing scales, which record the daily coal consumption of the plant, and delivered to another set of screw conveyers for conveyance to the driers. It has been found by experience that variation in the moisture content is most objectionable, particularly as it prevents a regular and controllable flow of the pulverized coal in the burners. As already stated, the results at Oneida-street show that drastic drying down to 1 per cent is not absolutely necessary, but not over 2 per cent is certainly preferable. The actual drying installation at Milwaukee consists of three separate cylindrical driers each of a capacity of 10 tons per hour, reducing the moisture in the Illinois coal from 10 per cent to 2 per cent. These driers are of the improved double-shell type, consisting of a long, slightly inclined, rotating double cylinder through which the coal passes by gravity, whilst the hot gases from a small furnace are passed between the inner and outer shell in opposite directions, the amount of coal used being about 1 per cent of the total dried from 10 per cent down to 2 per cent. This double drier has the advantages over the older single-drier type of greater capacity, increased efficiency and, especially, freedom from internal fires.

From the driers the coal is discharged into screw

conveyers, which convey it to bucket elevators, these in turn passing it on to other screw conveyers to be transferred to the dried-coal bunkers over the pulverizing mills.

Since the date of the installation of the Milwaukee plant, the Lopulco equipment has been further improved by the invention of a much simpler form of drying plant, a small stationary gravity drier which has now rendered obsolete the more complicated and expensive revolving plant hitherto always used. In this new drier which is being installed at the Cahokia plant, St. Louis, and the Vitry station, Paris, the crushed coal flows by gravity from overhead bunkers through the vertical stationary driers underneath. Through these about 10 per cent of the hot exit gases, diluted with air from the boiler plant so that the temperature does not exceed 215° F., are caused to circulate by means of a fan. This is an important feature, since if the temperature much exceeds 215° F. a slight volatilization of the volatile matter of the coal begins to take place. But with a temperature of 215° F. in the drying gas current the general temperature of the mass of the coal of course does not reach this figure. With the ordinary rotary drier the coal is heated to at least 250° F., causing a loss of volatile matter. The coal is thus dried as it passes straight through to the pulverizers under the driers, the speed of the coal travel simply being governed by the speed of the pulverizers, the whole operation of drying being rendered perfectly simple.

The two standard pulverizing mills in America are the Raymond and the Fuller, which are built in standard sizes of 2–6 tons per hour when grinding to 95 per cent through 100 mesh and 80 per cent through 200 mesh, with average bituminous coal containing less than 1 per cent of moisture, although these extreme figures are not generally necessary, as already stated.

The plant actually at Milwaukee consists of 8 pulverizers (both Raymond and Fuller types) each with a capacity of 6 tons of coal per hour, and driven with a direct-connected 100-h.p. motor, pulverizing the coal so that about 65 per cent would pass through a 200-mesh screen and 90 per cent through a 100-mesh screen, each pulverizing mill being also equipped with a fan for separating the powdered coal from the contents as soon as it has been reduced to a sufficiently fine state.

It is found by experience that the easy working of the pulverizing plant depends largely on efficient drying, in the sense of uniform moisture content, and thus on the ability of the drier attendants to dry each different quality of coal, from small pieces to dust, after passing the crusher, so that the amount of moisture continues the same. This, however, they soon learn by experience. The fan incorporated with the pulverizers then discharges the pulverized coal into overhead cyclone separators, where it falls by gravity into a screw conveyer at the bottom of the separator. It is then conveyed to the pulverized-coal bunkers, from which it is transferred to powdered-coal bins in the boiler house by an air system of conveying. This consists essentially of a hopper, high-speed screw, and a delivery nozzle, air being supplied at 40 lb. pressure to force the coal through small pipes. Although otherwise satisfactory, these conveyers were thought to use too much power for ideal working, and have since been replaced by screw conveyers.

From the storage bins in the boiler house the pulverized coal is conveyed to the burners by special Lopulco coal feeders. These consist essentially of a heavy cast-iron casing, forming the bottom of the pulverized-coal storage bin and containing a cast-iron screw feed driven through gear wheels by means of a variable-speed motor underneath, or, in the case of a duplex feeder, by a Reeves variable-speed device, by which the supply of pulverized coal can be regulated instantly as required. This screw conveys the pulverized coal to the end of the feeder, where it meets a current of air (at a pressure of 12 in. of water) passing through the inner wall of an annular orifice, the amount of air supplied in this way, to act primarily as a conveyer of the coal, being 10 per cent of the total required for combustion. At this point also the mechanism includes four agitators or paddles revolving at high speed in gear with the screw, so as to mix the air thoroughly with the pulverized coal. The mixing is, in fact, so intimate that from this point the mixture of coal and air acts practically as a heavy gas.

The mechanism of the coal feeder also includes an automatic cut-out so that when the air blast is shut off from the burners the coal-feed motor is also stopped automatically, so as to prevent plugging up the burners and pipes with pulverized coal.

There are several types of Lopulco burner, but at Milwaukee the six burners supplied to each boiler, facing in a downward direction, are of the heavy triplex pattern, composed of three rectangular chambers surrounded on four sides by air ports. Through the centre of each inner chamber is a $3\frac{1}{2}$-in. fuel nozzle terminating $9\frac{3}{4}$ in. from the outlet, so as to give the mixture a chance to expand before emerging into the furnace, instantaneous combustion resulting on combination with a supply of secondary air.

As already stated, 10 per cent of the air for combustion is supplied through the burner as a carrier for the coal, so that the secondary air amounts to 90 per cent of the total. This secondary air passes into the installation at the back of the furnaces and then through channels in the hollow furnace walls which it keeps cool whilst itself being heated, and enters the combustion chamber chiefly through ports or openings in the furnace front, as well as through air ports in the burner itself. The air is heated in its passage to various temperatures, depending on the portion of the hollow firebrick which it has traversed, but averaging 300° F.–700° F., and the supply is regulated by damper mechanism in each of the secondary air ports.

The latest principle, not adopted at Lakeside, is to preheat also the air conveying the coal from the feeder to the burner, this primary air supply being passed either through the side walls or under the bottom of the furnace. This method is stated to be particularly valuable in the case of undried coal, sometimes used when the moisture content is not over 5 per cent.

This arrangement of hollow air-cooled furnace walls, in addition to increasing the efficiency of the combustion by supplying heated air, is claimed to eliminate entirely

all excessive wear and tear on the brickwork, as will be discussed later.

The furnaces are 22 ft. wide and 14 ft. long, whilst the combustion space is very large, being 25 ft. high under the boiler tubes and 22 ft. under the arch. The design of the furnace is on the multiple-zone system, a feature of the Lopulco installations, in which three zones of differing intensity of heat are maintained. Just under the arch or roof of the furnace is the hottest zone of maximum combustion, whilst below this is the intermediate zone. The lowest stratum is a cooling zone, in which the temperature is constantly below that of the fusing point of the ash, chiefly because of the design of the secondary air admission.

In order to prevent any possibility of "slagging," an essential feature of the Lopulco design is the water screen, which cools the ash deposit, whilst at the same time the heat extracted is returned to the boiler. Much of the practical success of the Lakeside and other installations undoubtedly seems to be due, as already stated, to the efficiency of this water screen. The trouble is not only that the fine ash would otherwise fuse with the heat and corrode or "flux" the brickwork, but, as previously indicated, a change in the running conditions or a slight alteration in the quality of the coal causes the corrosive, molten mass to become sticky and refuse to flow off the brickwork, i.e. to slag, which has been a very serious obstacle to the success of pulverized fuel, because of the difficulty of removing the pasty, red-hot mass.

It will, of course, be understood that in some cases, both of generating stations and of ordinary power plants, coals are available that give no trouble in this respect and would work quite well without a water screen, but as a rule it is quite impossible to confine the coal to qualities in which the ash has a definite fusing point.

The water screen consists essentially of a series of 4-in. steel pipes in the lower part of the furnace. These pipes are an integral part of the boiler itself, being under full steam pressure and having the boiler water circulating through them, so as to cool the ash. The general arrangement is that part of the tubes are connected at one end with a header or the water drum of the boiler, and at the other to water boxes at the bottom of the furnace. From this header, pipes pass through the furnace and into another header, from which the circulation is continued to the drum or to the front header of the boiler.

The principal dimensions of the water-screen installation at Milwaukee as applied to each boiler are as follows :—

Number of tubes in water screen ..	22
Diameter of tubes	4 inches
Pitch of tubes	14 inches
Average length of exposed part of tubes	13¾ feet
Total heating surface of exposed part of tubes	320 sq. ft.
Total heating surface of boiler and water screen	13 380 sq. ft.

It is claimed that this water screen has practically eliminated slagging, so that a very wide range of fuels can be burned with any reasonable variation in boiler capacity, and enables guarantees to be given of an evaporation of 13·8 lb. of water per square foot of boiler heating-surface—a very remarkable figure.

Finally, as regards ash disposal, the plant is fitted with steam ash-ejectors to handle the very small amount of fine ash produced, the ash being taken through pipes direct from the combustion chambers and soot pits and discharged direct into railway wagons.

The generating plant at Milwaukee is of course outside the scope of this paper, but it may be stated that the present installation consists of two General Electric 20 000-kW, three-phase, 13 200-volt, 60-period, 1 800-r.p.m. turbines, calculated at 250 lb. steam pressure at the stop valve with 200 degrees F. superheat and 1 in. (absolute) back pressure, the rated power factor being 0·8. The auxiliaries for each 20 000-kW turbine are one 35 000 sq. ft., 3-pass condenser, one 24-in., 18 000-gallons-per-minute circulating-water pump driven by a 170-h.p. motor, another identical pump driven by a 170-h.p. steam turbine, one condensate pump driven by a 50-h.p. motor, one turbo air pump driven by a 100-h.p. motor, and one steam-jet air pump. Both pumps are required during the summer months when the water is warm, but only one in winter, and, as usual, the load is distributed equally between electrically-driven and steam-driven auxiliaries.

Finally, it is stated that since starting up in December 1920 the plant has been in continuous operation without a single hour having been lost through stoppages, although the new staff were not experienced in the use of pulverized fuel.

The New Installation at Vitry.

In connection with the Lakeside installation it will be of interest at this stage to insert a brief account of the Lopulco installation that is now in course of erection at the Vitry (Paris) power station of the Union d'Électricité, which will be the first very large, modern, pulverized-fuel installation in Europe, as well as including the largest water-tube boilers outside the United States. The plant consists of four Delauney-Belleville-Ladd boilers of 16 678 sq. ft. heating surface, each including a superheater and having steel-tube economizers of 9 684 sq. ft. heating surface, the boiler pressure being 256 lb./sq. in. (18 kg/cm^2) and the temperature of superheat 662° F. (350° C.), whilst the feed water is to enter the economizers at 140° F.

There is also included for each separate boiler a combined unit of one pulverizer with a duty of 6 tons of coal per hour, a vertical gravity drier of a maximum duty of 8½ tons of coal from 10 per cent to 2 per cent of moisture, one fan exhauster and trunking to remove by air separation the pulverized fuel from the pulverizing mills, 5 duplex fuel feeders to supply a regulated amount of pulverized fuel to a unit of two burners, and 10 triplex burners. In addition, of course, there are the water screens, hollow air-cooled furnace walls and very large combustion chamber on the same general lines as at Lakeside.

The guaranteed duty per boiler per hour is 140 580 lb. of water from and at 212° F., with a long overload period of 4 hours when the evaporation will be 210 870 lb.

of water from and at 212° F. This corresponds to 12 800 lb. of coal per boiler per hour (normal) and 19 700 lb. (overload), the calorific value of the coal used being 12 600 B.Th.U.'s (higher or gross value), corresponding to an evaporation of 10·98 lb. of water from and at 212° F. per lb. of coal on normal load, and 10·70 lb. on heavy overload, the guaranteed boiler-plant efficiency being 84 per cent at normal load. This is also equivalent to a normal evaporation of 8·4 lb. of water (from and at 212° F.) evaporated per sq. ft. of heating surface, or 12·6 lb. maximum, a very high capacity.

Finally, the power consumed in the preparation of the fuel, including handling, crushing, drying, pulverizing, air-separating and delivering to the burners, is guaranteed not to exceed 19½ kWh per ton of coal burnt, equal to, say, 1·0 per cent of the steam production of the plant. This figure depends, of course, on the efficiency of the generators, but in general it may be stated that in practice it will be actually less than 1 per cent of the steam output.

A Detailed Consideration of the Performance of Pulverized Fuel in Competition with Mechanical Stoking under the most Modern Conditions.

Difficulties of comparison.—It is somewhat difficult to compare the results of a modern pulverized-fuel equipment, such as that at Lakeside, with present mechanical-stoker practice from the point of view of a consideration of the relative merits in general of the two systems of firing.

The chief reason is that the Lakeside station is run on thoroughly modern and scientific lines, both of control and costing, but most large power stations in the world with mechanical stokers are not operated on anything even approaching these efficient methods. Thus, in very few power stations—at any rate in Great Britain—is there any real idea of the efficiency of the steam generation from week to week, nor are there even kept any very adequate records of the wear and tear and maintenance costs of the various sections of the plant, e.g. the mechanical stokers, the coal-elevating and conveying plant or the ash-handling plant, whilst practically nothing is known about the variations in the steam or power used auxiliary to the production of the steam, which may easily correspond to 3–5 per cent of the coal bill of the whole station, and often much more. Thus in many power station plants there is not even a boiler-feed meter in use, and, in general, little attempt is made to utilize feed meters, steam meters, pyrometers, CO_2 recorders or other instruments of precision on the right lines. Consequently, many of the conclusions arrived at as to the average performance of mechanical stokers are somewhat of a conjecture and may be unduly optimistic.

(1) *Efficiency figures.*

(*a*) *The present figures for mechanical stoking.*—It is particularly difficult to decide upon an average boiler-plant efficiency figure for mechanical stoking under the most modern conditions, and to state what advantages—if any—pulverized fuel possesses in this respect. In the first place there is no proper boiler-testing code or even standard methods of calculating the results. The author has considered this matter at length in his book on "Boiler Plant Testing," and he will therefore merely state that in Great Britain the situation is aggravated because what is supposed to be our standard code, that of the Institution of Civil Engineers, is so impractical that it is doubtful if anyone has attempted to carry out a test strictly according to its recommendations. The American Mechanical Engineers' code and the Continental code, primarily of the German Association of Engineers, are certainly better, but the utmost confusion exists on all kinds of points, such as—to mention only a few—whether the heat value of the coal is to be taken on the higher or lower figure, and, if the latter, what this means precisely, whether the auxiliary power is to be deducted in calculating the efficiency, and, if so, exactly what items; and also, if any corrections are to be made for variation in the heating value of the fuel over or under a given figure. For these and other reasons some confusion often exists even as to how the Lakeside figures of 85–86 per cent are calculated, and it must be remembered that a difference of, say, 3 per cent in the efficiency is easily possible, depending on how the various codes are interpreted in carrying out the test.

Further confusion also exists in Great Britain with regard to the unscientific American method of using the term "boiler horse-power." In reading the results of American boiler tests it has to be remembered that the American "boiler horse-power" means an evaporation of 34½ lb. of water from and at 212° F. per square foot of heating surface of the boiler. This arbitrary figure was adopted in 1876 at the Centennial Exhibition at Philadelphia because at that time the average steam engine took 34½ lb. of steam per indicated horse-power. Consequently, a "boiler horse-power" means an evaporation of enough water per square foot of heating surface to give 1 h.p. in the average American steam engine of 1876, i.e. 34½ lb. A boiler under American standards is allowed 10 sq. ft. of heating surface per horse-power, so that a boiler at normal American rating evaporates 3·45 lb. of water from and at 212° F. per square foot of heating surface, and in Table 7, for example, the rating of 137 per cent corresponds to 4·6 lb. of water per square foot of heating surface.

Another difficulty is that most boiler tests are carried out under what are practically abnormal and freak test conditions bearing little or no relation to the real everyday running. An efficiency of 80 per cent, for example, as obtained on such a test, less than 50 tons of coal being burnt for a few hours—which performance the majority of power station engineers believe applies to their plant all the year round—has nothing to do with the real results (more like 70 per cent) obtained with the burning of many thousands of tons of coal per annum. The point is that as results of 85–86 per cent are stated to be obtained at Lakeside regularly from week to week with pulverized fuel, what are to be taken as the corresponding yearly figures (apart from "official" test figures) for mechanical stoking with the plant performance recorded and calculated as nearly as possible under identical high-grade conditions?

The present all-the-year-round boiler-plant perform-

ance throughout the world, whether by hand or mechanical firing, and including many of the largest power stations, is deplorable. The author has carried out a large number of boiler-plant tests under actual working conditions during the past 15 years. Having referred to the results of these tests so often on previous occasions, he will only state that the net result of 400 separate tests undertaken in 41 different industries with 1 513 boilers, mostly of the Lancashire type, and burning 3 250 000 tons of coal per annum, was 58 per cent net working efficiency, including boilers, superheaters and economizers, and deducting the auxiliary steam or power used, the individual figures varying from 32½ to 82½ per cent. We are, however, here more directly concerned with the figures for water-tube boiler plants. In the first place, the general assumption that water-tube boiler plants are necessarily giving much better efficiency figures than cylindrical boiler plants has very little foundation in fact, and is almost on a par with the idea that power station boiler-plants are, in general, running at an efficiency of 80 per cent and evaporating 9–10 lb. of water per lb. of coal. The author's opinion, based also on the personal inspection of about 2 000 boiler plants, with an approximate total coal consumption of 15 000 000 tons per annum, including very many power station and water-tube boiler plants, is that the average figures at present obtained in Great Britain with water-tube boilers, of an average evaporation of 20 000 lb. of water per hour, can be classified as shown in Table 2.

TABLE 2.

Figures suggested by the Author as Representative Water-tube Boiler Practice (Mechanically Fired).

	Most efficient plant (5 per cent)	Average plant (85 per cent)	Bad plant (10 per cent)
(1) Duration of test, hours	12	12	12
(2) No. of boilers working	4	4	4
(3) Grate area (total), sq. ft.	560·0	560·0	560·0
(4) Coal used	Average	Average	Average
(5) Amount of coal used, lb.	137 275	141 040	139 765
(6) Calorific value of coal, B.Th.U.'s	12 000	12 000	12 000
(7) Percentage of ash in coal	10·5	10·5	10·5
(8) Coal burned per boiler per hour	2 859·9	2 938·3	2 911·7
(9) Coal burned per sq. ft. of grate area per hour, lb.	20·4	20·9	20·8
(10) Water evaporated, lb.	1 081 200	989 352	898 656
(11) Water evaporated per boiler per hour, lb.	22 525	20 611	18 722
(12) Water evaporated per lb. coal, lb.	7·87	7·01	6·43
(13) Equivalent evaporation from and at 212° F. per lb. coal, lb.	9·11	8·12	7·46
(14) Equivalent evaporation from and at 212° F. per 1 000 000 B.Th.U.'s, lb.	759·2	676·6	621·6
(15) Temperature of feed water before economizers, ° F.	110	110	110
(16) Temperature of feed water after economizers, ° F.	225	195	No economizer
(17) Coal bill saved by economizers, per cent	10·4	7·4	Nil
(18) Draught in back flue of boilers, in.	0·30	0·35	0·75
(19) Draught in chimney base, in.	0·65	0·50	0·75
(20) Temperature of flue gases before economizers, ° F.	450	475	575
(21) Temperature of flue gases after economizers, ° F.	250	200	—
(22) Percentage of CO_2 in flue gases	12·5	6·0	5·0
(23) Steam pressure, average, gauge, lb./sq. in.	160	155	150
(24) Temperature of saturation of steam, ° F.	370·5	368·3	365·9
(25) Temperature of superheated steam, ° F.	650·0	530·0	450·0
(26) Steam or power used auxiliary to the production of steam, per cent	1·5	2·0	2·5
(27) Thermal efficiency of plant:—			
(*a*) Net working efficiency, per cent	81·9	69·2	61·0
(*b*) Heat to boilers only, per cent	65·8	60·3	59·0
(*c*) Heat to economizers only, per cent	7·6	4·9	—
(*d*) Heat to superheaters only, per cent	9·7	5·4	2·6

That is to say, only 5 per cent of water-tube boiler plants are running with mechanical stokers at an efficiency of 80 per cent and over, whilst a reasonable average figure for 85 per cent of the plants is about 70 per cent, and the author would say further that in his opinion these figures are, if anything, on the optimistic side. The real state of affairs with regard to boiler-plant efficiency is now beginning to be realized.

It has been stated, for example, by more than one authority in the United States that the efficiency of the average modern mechanical stoker-fired boiler-plant in America does not exceed 65 per cent on regular performance, although a few hours' test on one boiler might give results of 75 per cent, and the fuel-economy campaign in the United States during the war revealed some astonishing facts. Recent investigations in Germany also bear these facts out, and the author would estimate that of the world's consumption of coal of, say, 1 250 000 000 tons per annum, about 500 000 000 cent, and Mr. Smoot feels that mechanical-stoker makers are not being treated fairly in the matter. That is to say, they supply a high-grade appliance which the customer will not work properly, the chief trouble being the failure to adjust the supplies of air and fuel.

With regard to excess air, it is very difficult to obtain authentic figures on this point. The very latest types of mechanical stoker are said to operate at 35–37½ per cent excess, although the average figure is probably 50–70 per cent, and in the case of hand-firing 75–100 per cent.

Table 3.

Figures of a 6 Months' Run (August 1921–January 1922) at Colfax Station, Duquesne Light Co., Pittsburgh, Pa.

	August	September	October	November	December	January	Average
Hours run	2 782	2 493	2 474	2 361	4 038	2 894	2 840
Total water evaporated, lb.	272 779 000	265 373 000	292 355 000	248 858 000	442 550 000	313 703 500	305 936 741
Total coal burned, lb.	30 085 600	28 023 100	31 690 300	27 109 300	48 790 600	35 911 530	33 601 738
Evaporation per lb. coal, lb.	9·06	9·46	9·22	9·17	9·07	8·73	9·10
Temperature of feed water, ° F.	208	210	203	204	193	204	204
Amount of superheat, degrees F.	124	120	127	127	132	136	128
Calorific value of coal, B.Th.U.'s	13 093	13 180	13 159	13 108	13 283	13 177	13 182
Average efficiency, per cent	76·4	78·9	78·0	77·2	76·8	77·6	77·5
Average rating, per cent	154	167	187	167	176	168	170
Exit flue-gas temperature, ° F.	466	460	465	467	478	471	468
Percentage of CO_2	9·2	9·3	9·6	10·3	11·2	11·1	10·1

Table 4.

Figures of a Typical Month's Run (December 1921) at Colfax Station, Duquesne Light Co., Pittsburgh, Pa.

Average calorific value of coal = 13 283 B.Th.U.'s. Average feed-water temperature = 193° F. Average superheat = 132 degrees F.

Boiler No.	Water evaporated	Coal burned	Time run	Efficiency	Average amount of CO_2	Exit gas temperature
	lb.	lb.	hours	per cent	per cent	° F.
1	60 020 000	6 638 060	559	76·6	9·9	489
2	55 291 000	6 089 230	480	76·9	12·0	482
3	75 435 000	8 319 030	696	76·7	10·3	460
4	75 542 000	8 324 290	691	76·8	11·9	481
5	32 242 000	3 519 710	285	77·5	11·5	—
6	73 474 000	8 138 360	688	76·5	11·7	479
7	70 546 000	7 761 900	640	77·0	11·0	481
Total	442 550 000	48 790 580	4 038	76·8	11·2	478

tons are used for the one purpose of steam generation at less than 60 per cent efficiency, corresponding to an avoidable loss of 100 000 000 tons of coal per annum.

As far as mechanical stokers are concerned, this is, of course, by no means altogether the fault of the stokers themselves. In a recent paper by Mr. Charles H. Smoot before the 1923 Convention of the American mechanical-stoker manufacturers, it is pointed out that most mechanical-stoker installations of any size in the United States will give a boiler-plant efficiency up to 80 per cent on test conditions, but that in practice few plants are running all the year round with an efficiency of 70 per

Let us consider, however, the relatively few mechanically-fired power station plants that are being run on the latest methods of control and that keep records of the weekly figures. Careful and long-period tests carried out, for example, at Connors Creek power station in America showed 75 per cent efficiency, and the Delaware station figures are 79·7–81 per cent, whilst exceptionally detailed tests at the Colfax plant, Duquesne Light Co., Pittsburgh, Pa., were given by C. W. E. Clarke, who designed the station, in a paper read before the American Society of Mechanical Engineers in December 1921.

The results of 6 months' run from August 1921 to January 1922 are represented in Table 3, while Table 4 gives the details for a particular month (December 1921), showing a result of about $76\frac{1}{2}$ per cent efficiency, the station always being under easy load conditions.

It is stated that the most efficient mechanically-fired power station in America is the Calumet plant of the Chicago Edison Company, but the author has not been able to ascertain the separate steam generation figures.

One of the most up-to-date power stations in Great Britain, both as regards design and equipment, and particularly from the point of view of scientific methods of control and continuous testing, is undoubtedly that at Dalmarnock, belonging to the Glasgow Corporation, and the author is indebted to Mr. R. B. Mitchell, the General Manager and Chief Engineer, for kindly supplying the fullest information as to the running of the station, and for giving every facility to examine on the spot the methods used. The arrangements for continuous testing, and the most modern methods of scientific control, including the keeping of a complete boiler-house log with full daily records, are hardly surpassed by any other station in the world.

The Dalmarnock station is, in common with Lakeside, intended eventually for 200 000 kW on full load with maximum output. At present half this installation has been erected. The boiler plant consists of two boiler houses, each containing 8 Babcock and Wilcox marine-type steel-cased boilers, arranged in 2 rows of 4 boilers each. These boilers are of 6 948 sq. ft. heating surface with an integral superheater of 2 452 sq. ft. heating surface, and work at 225 lb. pressure and 700° F. steam temperature, the ordinary evaporation being 50 000 lb. of water per hour at 150° F., and a long-period overload of 62 500 lb. Each boiler is also fitted with a cast-iron Green's economizer of 400 tubes of 5 155 sq. ft. heating surface, 14 ft. in length and $3\frac{1}{16}$ in. in diameter, on the new ring-stay pattern, heating the water from 150° F. to about 275° F.

The mechanical stokers are of two kinds, 36 Babcock and Wilcox forced-draught chain-grate stokers, and 12 Underfeed travelling grates, the total grate area per boiler being 273 sq. ft., consisting of 3 separate stokers each approximately 14 ft. 0 in. × 6 ft. 6 in. Each row of 4 boilers supplies (3 boilers working and 1 boiler as stand-by) a steam turbine of 15 000 kW ordinary load, and 18 750 kW long-period overload, and 5 of these are installed for the 4 rows of boilers so as to have one turbine as a stand-by, although, of course, 16 boilers and 5 turbines can be worked if desired. It is impossible to describe in the space available the elaborate nature of the methods of scientific control adopted. Briefly, however, the station is operated from a central control room, which is in communication with the boiler house and the turbine house by means of a complete equipment of marine signalling-apparatus and marine loud-speaking telephones. Each boiler is regarded as a separate unit as regards testing instruments, and is equipped with three Avery 2-cwt. automatic coal-weighing machines, one for each stoker, CO_2 indicator, complete draught gauge and pyrometer equipment, and British Thomson-Houston steam meter for the output of the boiler, together with a Lea **V**-notch recorder connected to a turbo-alternator for each of the 4 boilers.

The coal is also sampled and analysed continuously, being of inferior quality, averaging 10 500 B.Th.U.'s in the laboratory attached to the station, and the figures of the performance are plotted every shift all the year round. The plant is also provided with an ingenious and most accurate arrangement of two very large, calibrated, steel test-tanks each having a capacity of 28 000 lb. of water, so that weighed-tank tests can be quickly carried out, and the performance of the turbines is controlled in an equally scientific manner.

The guaranteed overall efficiency of the plant, using the inferior 10 500-B.Th.U. coal, including the boilers, superheaters and economizers, is 80 per cent, although this is presumably for short official test-figures only, and not for continuous running, whilst there also seems to be the usual confusion as to the exact meaning of the figure.

As regards the actual running results from day to day all the year round, the figures given in Table 5

TABLE 5.

Actual Operating Boiler House Statistics (One Day), taken at Dalmarnock Power Station; Friday, 21st September, 1923.

Total coal consumed, lb.	1 112 160
Calorific value as fired, B.Th.U.'s	9 905
Total ashes removed, lb.	141 689
Ashes, per cent of total coal	12·74
Total condensate, lb.	6 866 758
Total make-up water, lb.	384 011
Total water evaporated, lb.	7 250 769
Average boiler pressure, lb./sq. in.	275
Average steam temperature, ° F.	676
Average of CO_2 recorded, per cent ..	11·0
Temperature of flue gases leaving economizers, ° F.	372
Temperature of water entering economizers, ° F.	161
Temperature of water leaving economizers, ° F.	286
Water evaporated per lb. coal, lb... ..	6·51
Coal per kWh generated, lb.	1·82
Water per kWh generated, lb.	11·88
Make-up water, per cent	5·60
Boiler-house efficiency, per cent	78·4

and supplied by Mr. R. B. Mitchell are typical for a recent date in September 1923.

Some further interesting information supplied by Mr. Mitchell was published in *Engineering*, 1st September, 1922. These figures embody the detailed results of 84 consecutive 8-hour shifts (4 weeks' run) with an aggregate output of 9 784 000 kWh, varying from 30 000 to 230 000 kWh per shift. During this month the average heating value of the coal was 10 500 B.Th.U.'s and the temperature of the feed water was 141° F., the steam pressure being 275 lb. (gauge) with a temperature of 700° F.

The results show that at a load of only 50 000 kW

for an 8-hour shift, the coal consumption was 2·116 lb. per kWh, and as the load increased to the maximum output this figure was reduced to 1·816 lb. per kWh. The performance of the station is approaching the maximum, and with everything under the best conditions an ideal evaporation of 6·722 lb. of water per lb. of 10 500-B.Th.U. coal, corresponding to a boiler plant efficiency of 80·92 per cent, together with 11·535 lb. of steam per kWh, will be attained.

It may be noted that when the station is doing no useful work the total constant losses due to banking up, condensation, radiation, etc., only correspond to an average of about 20 000 lb. of coal per 8 hours, being 5 123 lb. in the boiler plant and 14 877 lb. in the generating plant.

Mr. Mitchell, further, has very kindly supplied the author with the returns for the last financial year, 1922–3, in which the average boiler-plant efficiency for 52 consecutive weeks at the Dalmarnock station is 76·6 per cent. The figures are as follows:—

Total units generated	171 827 337
Average load, kW	19 600
Maximum load, kW	58 500
Load factor, per cent	33·4
Total coal consumed, tons	142 942
Coal per unit generated, lb.	1·86
Coal per unit delivered, lb.	1·95
Station efficiency (units generated), per cent	17·5
Boiler-house efficiency (52 readings), per cent..	76·6

As representative also of the figures obtained on special short tests, we have those given in Table 6, carried out on two boilers in March 1923, being in one case with induced draught and in the other with balanced draught, the figures being expressed for the two boilers as one compound unit.

We may therefore take as representative of the best conditions of mechanical stoking with poor quality coal the figures obtained at Dalmarnock, which indicate —as the result of the most elaborate tests—an all-the-year-round efficiency of 76·5 per cent on a poor load factor of about 34 per cent. Also, on theoretically the ideal load factor, the limiting efficiency is about 81 per cent. It is obviously very difficult to decide upon absolutely fair average figures, but the author feels that the efficiency of Dalmarnock could be taken as, say, 78 per cent with a 60 per cent load factor, emphasizing again, of course, that this applies to continuous week-in and week-out running all the year round, and not to official tests.

This comparison between Lakeside and Dalmarnock is, in fact, probably as good as can be obtained for the rival systems of firing. Both stations are designed for 200 000 kW, Dalmarnock now having approximately 75 000 kW easy working and 93 750 kW long overload, whilst Lakeside is running on 40 000 kW (50 000 kW overload). The present extensions to the latter will be completed in a few months, when the figures will be 80 000 kW and 100 000 kW respectively. The turbines at Lakeside are somewhat bigger, i.e. 20 000 kW as compared with 15 000 kW, but the boilers are nearly twice the size, in this respect truly representative of American practice as compared with British. The coal used in both cases is of inferior quality, that at Lakeside being 11 500 B.Th.U.'s and that at Dalmarnock 10 500 B.Th.U.'s, but unfortunately the load factors are very different, viz. 60 per cent at Lakeside and 34 per cent at Dalmarnock, because of bad trade in the Glasgow area. However, it will not be easy in practice to obtain a better general comparison.

Another point also of the greatest importance is that during the past five or six years, largely due in fact to the keen competition of pulverized fuel, considerable improvements have been made in the general principles of mechanical stoking, which was thought to have reached practical perfection. In the first place, there has been an enormous increase in furnace volume, and British power station practice in general has fallen hopelessly behind that in America in this respect. One of the chief causes of the inefficiency of the mechanically-fired boiler plants in Great Britain is that the tubes of the boiler are far too near the furnace, so that the flames touch the boiler long before the combustion is completed, and the reactions are at once damped down with the escape of unburnt fuel. The mere fact, therefore, of doubling or trebling the volume of the combustion chamber would result in greatly improved results with mechanical stoking. A feature of pulverized-fuel firing is, of course, the enormous combustion volume, at least 1 cubic foot of space for each 3 lb. of coal burned per hour.

Secondly, there has been the perfecting of the stoker itself; for example, the "compartmenting" of the air supply in the travelling grate stoker so as to adjust independently the amount of air passing at every stage in the length. Again, a very important new factor is that of air heating, which is now just being realized, and which is under consideration at Dalmarnock for the future boiler-houses Nos. 3 and 4. As yet there are only three or four plants of any considerable size equipped with air heaters in Great Britain and France, and in the United States not a single plant other than an odd boiler as an experiment. Further, so far as the author is aware, no mechanically-fired plant has yet adopted hollow air-cooled furnace walls (except in a very small section of the brickwork) and used the heated air for secondary combustion. It is interesting to note also that ordinary air-heating in addition is being considered for pulverized fuel at the Colfax station.

The author is quite prepared to admit that if Dalmarnock, for example, could be altered on these lines, a considerable improvement on 78 per cent efficiency (regular performance) at 60 per cent load factor would result, and that air-heating alone might bring the figure up to over 80 per cent. Also, he is aware that figures approaching 85 per cent are now being guaranteed in Great Britain with mechanical stokers. For example, the efficiency of one plant in London, with mechanical stokers, air heaters, superheaters and economizers, has been guaranteed to be 85 per cent on the higher value of the coal, after deducting the auxiliary steam or power, which is not to exceed the equivalent of $1\frac{1}{4}$ per cent of the evaporation of the plant. An article by the author in the *Electrician* on this plant and the uncertainty as to what these figures meant led

TABLE 6.

	Induced draught		Balanced draught	
(1) Date of test	20/3/23		21/3/23	
(2) Duration of test	6 hours		3 hours	
(3) Boilers	Nos. 9 and 10		Nos. 9 and 10	
Coal.				
(4) Analysis of coal used (mixed pearls and singles):—	As fired	Dry	As fired	Dry
(a) Moisture, per cent	12·9	—	14·8	—
(b) Volatile matter, per cent	24·0	27·5	23·6	27·75
(c) Fixed carbon, per cent	44·0	50·5	42·5	50·00
(d) Ash, per cent	19·1	22·0	19·1	22·25
(e) Dry calorific value, B.Th.U./lb.	11 630		11 520	
(f) As fired, calorific value, B.Th.U./lb.	10 130		9 802	
(5) Total coal weighed, lb.	112 000		64 512	
(6) Sample for analysis, lb.	104		116	
(7) Total riddlings, lb.	1 678		1 086	
(8) Total coal in riddlings, lb.	1 050		789	
(9) Ashes removed from ash-pits, lb.	14 560		7 168	
(10) Ashes removed, in per cent of coal	13·2		11·28	
(11) Total coal consumed, lb.	110 846		63 607	
(12) Average coal consumption per hour, lb.	18 474		21 202	
Water.				
(13) Total water evaporated, measured by Lea recorder, lb.	760 773		426 372	
(14) Total water evaporated, measured by steam flow, lb.	744 000		420 100	
(15) Average evaporation per hour (Lea recorder), lb.	126 795		142 124	
(16) Average evaporation per hour (steam meters), lb.	124 000		140 700	
(17) Average temperature of feed water at economizer inlet, ° F.	166·5		158·0	
(18) Average temperature of feed water at economizer outlet, ° F.	284·0		272·5	
(19) Average temperature-rise of water, degrees F.	117·5		114·5	
(20) Actual evaporation per lb. coal, lb.	6·86		6·7	
Steam.				
(21) Average boiler pressure, lb./sq. in. (g.)	273·2		274·0	
(22) Average total temperature, ° F.	655·0		672·0	
(23) Average degrees superheat, degrees F.	241·3		258·0	
(24) Factor of evaporation	1·245		1·248	
Gases.				
(25) Average temperature of air entering grates, ° F.	80		(at forced-draught duct) 60	
(26) Average temperature of gases at economizer inlet, ° F.	600		634	
(27) Average temperature of gases at economizer outlet, ° F.	399		414	
(28) Average temperature-drop of gases, degrees F.	201		220	
Gas Analysis by Orsat.				
(29) Average CO_2 content, per cent	13·00		14·5	
(30) Average O_2 content, per cent	6·02		5·5	
(31) Average CO content, per cent	0·28		0·3	
Draught (inches of water).				
(32) Average at forced draft duct, in.	—		+ 1·8	
(33) Average beneath grates, in.	− 0·10		+ 0·22	
(34) Average over fire front, in.	− 0·15		− 0·06	
(35) Average over fire back, in.	− 0·43		− 0·30	
(36) Average at uptake, in.	− 1·15		− 0·90	
(37) Average at chimney, in.	− 1·60		− 1·20	
Auxiliaries.				
(38) Total kWh, induced-draught fan	410		150·0	
(39) Total kWh, No. 9 forced-draught fan	—		47·5	
(40) Total kWh, No. 10 forced-draught fan	—		47·3	
(41) Total kWh, stoker drive (calculated)	50		25	
(42) Total kWh, electrical feed pump (calculated)	450		225	
Total kWh	910		495·0	
Principal Results.				
(43) Coal consumed per square foot of grate area per hour, lb.	33·8		38·8	
(44) B.Th.U.'s liberated per square foot of grate area per hour	342 394		375 416	
(45) B.Th.U.'s transferred per lb. of coal of 10 130 B.Th.U.'s	8 293·7		—	
(46) B.Th.U.'s transferred per lb. of coal of 9 802 B.Th.U.'s	—		8 189·0	
(47) B.Th.U.'s transferred per square foot of total heating surface per hour	5 256·9 (equivalent to 4·35 lb. water)		5 963·3 (equivalent to 4·88 lb. water)	
(48) Actual evaporation, lb. of water per lb. of coal	6·86		6·70	
(49) Equivalent evaporation from and at 212° F.	8·54		8·36	
(50) Equivalent evaporation from and at 212° F. per 10 000 B.Th.U.'s in coal	8·43		8·525	
(51) Cost of evaporating 10 000 lb. water from and at 212° F., coal at 16s. per ton	8s. 4·3d.		8s. 4½d.	
Heat Balance per lb. of Coal.	B.Th.U.'s	Per cent	B.Th.U.'s	Per cent
(52) To calorific value of coal as fired	10 130	100·00	9 802	100·00
By heat transfer in boiler	6 530·7	64·47	6 458·0	65·90
By heat transfer in superheater	953·5	9·45	964·0	9·84
By heat transfer in economizer	809·5	8·00	767·0	7·82
By heat transfer in combined plant	8 293·7	81·92	8 189·0	83·56
By heat loss in flue gases	1 240·0	12·25	1 195·0	12·20
By heat loss in moisture	159·0	1·57	150·0	1·50
By heat loss in combustible in ash	108·3	1·07	negli	gible
By heat loss in radiation	252·0	2·50	245·0	2·50
By heat loss due to CO, heat in ashes, moisture in air, combined hydrogen and other losses unaccounted for	77·0	0·69	23·0	0·24
	10 130	100·00	9 802	100·00

to correspondence in the columns of that journal during March, April and May, 1923. It is possible that such figures may be attained on a short test of a few hours, but when it is remembered that they imply continuously about 37¾ per cent excess air, 12 per cent CO_2, and a temperature of the final-exit flue gases in the chimney base of about 235° F., it is fairly obvious that they will not be the weekly figures all the year round.

Bearing in mind, therefore, the difficulties of the whole question and the natural differences of opinion on a matter so complicated, the author considers that a fair figure for the net yearly working efficiency of a mechanical-stoker plant under the most modern conditions, with superheaters, economizers, air heaters, large furnace volume, hollow furnace walls or any other equipment, combined with the most scientific supervision obtainable, and with average working conditions, particularly quality of fuel and load factor, is 81–82 per cent, including the higher value of coal and deducting all auxiliary power, which corresponds to about 40 per cent excess air.

(*b*) *The Lakeside figures*.—As regards the figures obtained with pulverized fuel at Lakeside, the net results are 85–86 per cent actual working efficiency, month in and month out, on the comparatively low-grade Illinois coal of about 11 500 B.Th.U.'s per lb. (high calorific value). These figures are based in the first place on a most elaborate series of special tests carried out under actual running conditions, probably unsurpassed in the world for care and accuracy and for the time and trouble taken. Secondly, they are the results of continual weekly records taken as part of the routine of the station control, and, so far as the author is aware, the Lakeside station is the only one in the world that publishes regularly, monthly and quarterly, the full details of the boiler-plant performance.

In May and June 1923, for example, the weekly figures averaged 86–87 per cent, and on one special test carried out under abnormal conditions on one boiler 89·1 per cent was reached, the highest recorded figure for a coal-fired plant. From these facts, therefore, it is clear that the Lakeside station contains the most efficient steam-generation plant in the world.

The modern Lopulco guarantee alone for pulverized fuel is 84–86 per cent, or 82–84 per cent without economizers under test conditions, a remarkable figure when it is remembered that such guarantees must always be on the conservative side. The exact figure depends of course on the particular circumstances, such as the quality of the coal, the nature of the equipment, the size of the boilers, and the fluctuation in the evaporation. As already stated, the guarantee at Vitry, for example, is 84 per cent.

At the new Cahokia station of the Union Electric Co., on the southern bank of the Mississippi, for supplying St. Louis, the capacity of which will eventually be 300 000 kW—the present section under construction being 8 boilers of 17 800 sq. ft. heating surface and an evaporation of 170 000 lb. from and at 212° F. for each boiler, corresponding to 10·40 lb. of water per sq. ft. of heating surface and 14·00 lb. for peak loads—the guarantee is 85 per cent. In the Cleveland contract, where four boilers—the biggest in the world—are being installed, having 30 600 sq. ft. heating surface and evaporating over 300 000 lb. of water from and at 212° F. per hour, the guaranteed efficiency is 85·4 per cent without economizers. The most interesting figures, however, in this respect are perhaps those for the new Trenton Channel station of the Detroit Edison Co. This installation is to consist of 6 boilers of 29 000 sq. ft. heating surface (say 290 000 lb. evaporation per hour, normal), and the guarantees are as follows:—

Evaporation, lb. water from and at 212° F. per sq. ft. heating surface	Efficiency
lb.	per cent
3·5	87·5
6·9	88·0
10·3	86·5
13·8	83·0

Thus with the enormous figure of 13·8 lb. of water per sq. ft. of heating surface, that is 400 000 lb. of water per boiler per hour, without economizers, the guarantee is 83 per cent and for normal working 86½–88 per cent. It is expected that both at Cahokia and Lakeside the average efficiency will be 88¼ per cent on normal output when the plants are completed.

Finally, with regard to the installation of pulverized coal now being erected at Colfax, the efficiency guarantee is 89 per cent, using air heaters. It is expected to obtain a performance of less than 16 000 B.Th.U.'s per kWh on test, and under 17 500 B.Th.U.'s on long periods. With the present mechanical stoking the best figures are 18 713 B.Th.U.'s for 90-day periods, but normally 19 000 B.Th.U.'s. At Dalmarnock the figure is approximately 19 900 B.Th.U.'s.

Typical of the extensive series of tests carried out at Lakeside are the condensed figures given in Table 7 for 15 trials of 17·6–42·3 hours' duration.

The detailed figures of 5 tests on one boiler, at different ratings, as set out in Table 8, give a good idea both of the performance of pulverized fuel under modern conditions, and of the elaborate care and attention to detail with which these tests at Lakeside have been carried out.

As seen from the figures, these elaborate tests were carried out at greatly different duties, varying from evaporations of 53 390 to 92 202 lb. per hour, the normal rating being 90 000 lb., and the coal consumption varying from 5 960 to 11 350 lb. per boiler per hour. The detailed efficiency and heat balance-sheet figures show an efficiency of 84·6 per cent for the whole plant at the high rating of 92 200 lb. of steam per hour, corresponding to about 85–86 per cent for normal rating and varying from 84·6 to 89·1 per cent. In general, therefore, it may be stated that the Milwaukee boiler plant is running at the extraordinarily high efficiency of about 85 to 86 per cent, and the previous general ideas of 82½–85 per cent efficiency with pulverized fuel on test figures have been far exceeded. Scheffler and Barnhurst, for example, in their 1919 paper stated that a pulverized-fuel plant ought to work all the year

round at 75 per cent efficiency, corresponding to an average saving of 12–15 per cent in the coal bill as compared with mechanical stoking.

It will be noted that the economizers reduce the flue-gas temperature from about 430°–496° F. leaving the boiler (a very low figure, showing the efficiency of working) to about 168°–251° F., whilst the feed water is raised from 124°–127° F. to 168°–195° F.

As regards draught, the figure varies from 0·525 to 2·38 inches of water leaving the economizer, but at normal running it is about 1¾–2 inches, whilst the water evaporated per lb. of coal varies from 8·12 to 8·92 lb., being about 8¼ lb. for normal working.

The actual amount of air used in excess of the theoretical was determined with particular care, and, as will be seen, this varied from 10·7 to 25·2 per cent, depending on the evaporation of the boilers. The figures in this respect can be stated to be approximately 25 per cent excess air for 5 per cent overload, about 22 per cent on normal load and 12½ per cent on only 60 per cent of full load, although it is extremely difficult to determine the figures accurately. In general, therefore, the old contention that pulverized coal is working with only 20 per cent excess air can be accepted as correct.

The analysis of the flue gases is given for the fourth pass of the boiler, the result being 14½–16 per cent CO_2, a very high figure, equal to about 16 to 17 per cent at the actual point of combustion, whilst the amount of CO present is nil, which is also found to be characteristic of pulverized-fuel firing because of the intimate mixture of air and fuel and also the high temperature. The air leakage in the plant, which it is almost impossible to prevent with any method of firing, is indicated by the fact that the CO_2 is down to 10½–13 per cent on leaving the economizer. The amount of this air leakage is not generally realized by power station engineers.

(*c*) *Comparison of pulverized-fuel stoking and mechanical stoking.*—The net result, therefore, allowing conservative figures, is that under the most modern conditions pulverized fuel is working at 86 per cent efficiency and mechanical stoking at 81½ per cent, the saving in the coal bill due to the former method being thus 5½ per cent. This, however, though strictly correct, is certainly rather unfair to pulverized fuel from a practical point of view.

There seems to be no question in the first place that it is very much easier to obtain the highest efficiency with pulverized fuel. To run a mechanically-fired boiler plant all the year round at 81½ per cent efficiency, including the comparatively heavy stand-by and banking-up losses, requires almost superhuman attention, both in equipment and control, and only one or two stations in the world are attaining such a figure. It is admitted, of course, that the attention at Lakeside is far above the ordinary, but the main point seems to be that, with what may be termed extremely good attention, pulverized fuel would probably give, say, 82½ per cent efficiency, the mechanical stoker-plant figure being taken as 75 per cent, equivalent to a difference of 9 per cent in the coal bill. Of course, if pulverized fuel were adopted in the average existing station, the saving would be something like 15–20 per cent.

The chief reasons why pulverized fuel gives a decidedly higher efficiency than mechanical stoking seem to be the reduced excess of air (because of the much more

TABLE 7.

*A Summary of the Tests carried out on Boiler No. 8 at Lakeside by the United States Bureau of Mines for the Combustion Engineering Corporation, under the Supervision of Henry Kreisinger.**

Test no.	Duration	American rating	Water evap. per sq. ft. heating surface per hour	Effy. of boiler and superheater	Effy. of boiler, superheater and economizer	CO_2 exit gases from boiler	Temp. of flue gases leaving boiler	Temp. of flue gases leaving economizer
	hours	per cent	lb.	per cent	per cent	per cent	° F.	° F.
1	42·3	137	4·6	83·3	86·3	15·8	434	168
2	24·0	215	7·4	82·6	87·1	14·6	475	196
3	20·0	209	7·2	82·5	87·0	14·7	482	205
4	24·7	146	5·0	85·4	89·1	16·0	430	204
5	24·2	236	8·1	79·8	84·6	14·1	496	251
6	28·2	139	4·8	83·8	88·0	15·1	454	229
7	25·6	177	6·1	83·7	88·0	14·7	466	242
8	24·0	175	6·0	85·2	89·6	15·1	468	239
9	24·3	204	7·0	83·9	88·3	15·1	487	256
10	24·6	203	7·0	83·0	87·0	14·7	474	256
11	24·1	244	8·4	80·2	85·0	14·0	530	286
12	23·9	241	8·3	81·7	86·4	14·2	524	263
13	24·2	251	8·6	81·0	85·6	14·2	531	272
14	24·5	130	4·5	84·7	88·5	17·1	435	218
15	17·6	137	4·7	84·4	88·4	16·4	440	221

* The coal used was either dried Illinois, or undried Illinois, Pennsylvania and Ohio.

TABLE 8.

Summary of Results of 5 Boiler Tests with Pulverized Illinois Coal.

Tests made on Boiler No. 8, Lakeside Station of the Milwaukee Electric Railway and Light Company.

(1) Test no.	1	2	3	4	5
(2) Duration, hours	42·33	23·97	19·92	24·40	24·17
Coal as Fired.					
(3) Per cent through 100 mesh	89·2	90·8	90·5	92·2	90·5
(4) Per cent through 200 mesh	67·7	68·7	69·1	70·5	66·7
(5) Moisture content, per cent	2·25	3·56	3·59	5·24	5·61
(6) Volatile matter, per cent	36·00	36·48	35·66	36·30	35·25
(7) Fixed carbon, per cent	49·60	48·33	48·70	46·10	47·16
(8) Ash, per cent	11·55	11·63	12·05	12·36	11·38
(9) Sulphur, per cent	2·26	2·74	2·28	3·91	3·30
(10) Hydrogen, per cent	4·97	5·18	5·01	5·10	5·06
(11) Carbon, per cent	68·88	67·20	66·22	63·44	65·41
(12) Calorific value, B.Th.U.'s	12 321	12 022	11 917	11 488	11 661
(13) Total fuel fired, lb.	253 161	233 477	190 334	160 881	274 640
(14) Fuel fired hourly, lb.	5 980	9 740	9 560	6 650	11 350
(15) Fuel fired hourly per cubic foot combustion space	0·85	1·39	1·36	0·95	1·62
Ash and Refuse.					
(16) Carbon in 2nd- and 3rd-pass refuse, per cent of coal fired	3·60	5·06	5·06	5·31	7·17
(17) Carbon in uptake dust, per cent	6·26	5·09	3·30	2·82	5·95
(18) Unburned carbon per lb. coal, per cent	0·45	0·45	0·40	0·40	0·74
Ash Account.					
(19) From bottom of furnace, lb.	6 240	6 141	5 230	4 420	1 000
(20) From 2nd and 3rd pass, lb.	13 565	12 236	9 278	8 260	12 270
(21) Determined from dust-collector data, lb.	10 580	8 640	8 632	7 290	18 120
Air.					
(22) Temperature of air entering furnace, ° F.	86	89	91	104	93
(23) Pressure of air of feeders, in. of water	11·0	12·2	13·6	12·2	13·6
(24) Air entering with coal, per lb. coal, lb.	2·05	1·25	1·27	1·85	1·03
(25) Air entering at burners, per lb. coal, lb.	—	—	—	2·07	—
(26) Air through hollow wall, per lb. coal, lb.	—	—	—	5·64	—
(27) Excess air in flue gases, per cent	13·3	21·9	21·2	10·7	25·2
Flue Gas.					
(28) Carbon dioxide in 4th pass, per cent	15·8	14·6	14·7	16·0	14·1
(29) Oxygen in 4th pass, per cent	3·3	4·6	4·6	3·3	5·2
(30) Carbon monoxide, 4th pass, per cent	0·05	0·0	0·03	0·0	0·09
(31) Carbon dioxide entering economizer	—	12·6	12·6	14·4	11·5
(32) Carbon dioxide leaving economizer	10·4	11·9	12·0	13·2	10·8
(33) Dry gas per lb. coal leaving boiler, lb.	11·04	11·63	11·37	10·06	11·56
(34) Dry gas per lb. entering economizer, lb.	—	13·36	13·16	11·14	14·10
(35) Dry gas per lb. leaving economizer, lb.	16·45	14·11	13·80	12·07	15·01
(36) Temperature of flue gases leaving boiler, ° F.	434	475	482	430	496
(37) Temperature of flue gases entering economizer, ° F.	338	400	424	400	431
(38) Temperature of flue gases leaving economizer, ° F.	168	196	205	204	251
Draught.					
(39) At furnace, inches of water	0·017	0·19	0·16	0·045	0·206
(40) In 4th pass, inches of water	0·314	1·11	1·185	0·39	1·40
(41) Entering economizer, inches of water	0·424	1·23	1·28	0·40	1·66
(42) Leaving economizer, inches of water	0·525	1·67	1·72	0·51	2·38
Steam and Water.					
(43) Steam pressure, lb./sq. in. (abs.)	276	280	280	276	281
(44) Superheat, degrees F.	137·40	180·80	186·80	118·40	178·60
(45) Total water fed to boiler, lb.	2 260 018	2 012 452	1 615 530	1 393 250	2 228 514
(46) Water fed to boiler per hour, lb.	53 390	83 953	81 121	57 572	92 202
(47) Water evaporated per lb. coal, lb.	8·92	8·62	8·49	8·66	8·12
(48) Heat absorbed per lb. water, boiler and superheater	1 149·60	1 151·00	1 158·40	1 132·00	1 146·60
(49) Temperature of feed water entering economizer, ° F.	126	129	124	126	127
(50) Temperature of feed water entering boiler, ° F.	168	192	188	175	195·4
Rates of Heat Absorption.					
(51) Rating developed, per cent	137	215	200	147	236
(52) Horse-power developed	1 833	2 886	2 798	1 946	3 156

	B.Th.U.'s	Per cent	B.Th.U.'s	Per cent	B.Th.U.'s	Per cent	B.Th.U.'s	Per cent	B.Th.U.'s	Per cent
Heat Balance, Boiler.										
(53) Heat absorbed by boiler and superheater	10 260	83·3	9 924	82·6	9 835	82·5	9 803	85·4	9 309	79·8
(54) Loss carried away in dry gases	928	7·5	1 086	9·0	1 076	9·0	794	6·9	1 130	9·7
(55) Loss: steam from burning hydrogen	511	4·2	524	4·3	506	4·3	480	4·2	488	4·2
(56) Loss: steam from moisture in coal	27	0·2	43	0·4	44	0·4	62	0·5	69	0·6
(57) Loss: steam from moisture in air	10	0·1	10	0·1	13	0·1	21	0·2	23	0·2
(58) Loss: by carbon monoxide	22	0·2	0	0·0	14	0·1	0	0·0	42	0·4
(59) Loss: carbon in ash and flue dust	66	0·5	62	0·5	59	0·5	59	0·5	108	0·9
(60) Loss: radiation	166	1·4	125	1·1	125	1·1	147	1·3	114	1·0
(61) Loss: errors and unaccounted for	331	2·6	248	2·0	245	2·0	125	1·0	378	3·2
(62) Total	12 321	100·0	12 022	100·0	11 917	100·0	11 491	100·0	11 661	100·0
Heat Balance, Economizer.										
(63) Total heat supplied. (Items 54–57)	1 476	12·0	1 663	13·8	1 639	13·8	1 357	11·8	1 710	14·7
(64) Heat absorbed by economizer	375	3·0	543	4·5	543	4·5	432	3·8	556	4·8
(65) Loss: dry gases delivered from boiler	219	1·8	301	2·6	314	2·6	244	2·1	444	3·8
(66) Loss: air leaking into economizer	107	0·9	63	0·5	67	0·6	49	0·4	132	1·1
(67) Loss: water vapour	483	3·9	506	4·2	491	4·1	493	4·3	505	4·3
(68) Total heat accounted for	1 184	9·6	1 413	11·8	1 415	11·8	1 218	10·5	1 637	14·0
(69) Radiation and unaccounted for	292	2·4	250	2·0	224	2·0	139	1·2	73	0·7
(70) Heat absorbed by boiler and economizer	10 635	86·3	10 467	87·1	10 378	87·0	10 235	89·1	9 683	84·6

intimate mixture of the fuel and air); the very high temperature of the combustion, combined with more intense radiation; the continual presence of a finely divided cloud of incandescent ash and burning fuel in the combustion chamber; and the perfectly even diffusion and distribution of the heat to every part of the boiler tubes.

The reduced excess air, 20–22 per cent, as compared with, say, 35–37½ per cent, means in the first place a very high CO_2 content, viz. 16–17 per cent, at the actual combustion. As is well known, it is not possible to work mechanical stokers with over 14–15 per cent CO_2, even with the most unusual attention, and of course the average figure is much less than 10 per cent, especially on chain-grate stokers, so that pulverized fuel has a considerable advantage in this respect. Reduced excess of air also means a continual high temperature of combustion, averaging over 2 000° F. with pulverized fuel, the figure at the River Rouge plant, for example, being 2 100° F., mixed blast-furnace gas and pulverized fuel being burnt, and, as already stated, one of the practical problems has been to get the brickwork to withstand the conditions. The very large combustion chamber means a slowing down and great expansion of the air-fuel mixture, so that, in addition to the intimate mixing, the combustion has ample time to complete itself, incidentally without friction loss against the brickwork.

Another factor which probably plays an important part is that the whole volume of the combustion chamber is continually filled with a cloud of highly incandescent ash, which would appear to act on the principle of the incandescent mantle in greatly increasing the radiation effect, over and above that of the furnace walls. As is well known, the secret of working a boiler plant efficiently by any method of firing is to have the maximum radiant heat and, consequently, the highest furnace temperature. Finally, the combustion is in direct and intimate contact with the boiler tubes, without any arches or baffles.

(2) *Unburnt material in the ash.*—There is no question that one of the practical advantages of pulverized fuel is the much more thorough combustion in the ash. The final results of the detailed tests at Lakeside, including many samples of ash taken from different stages of the plant, was 0·40–0·74 per cent unburnt carbon, and the general figure is considerably less than 1 per cent of the weight of the coal.

It is very difficult to get authentic figures for the loss caused by the amount of unburnt and partially burnt fuel in the ash and clinker with mechanical stoking. The amount of fuel in the riddlings from mechanical stokers in many power stations is very large, and quite often the net loss is easily 4–5 per cent of the coal bill, largely owing to carelessness in not re-burning the riddlings.

In one case in the author's own experience a power station was selling ashes to a large factory a short distance away for a few pence per ton for road-making purposes, and the factory was actually using the material in their cylindrical boilers for steam generation.

Some types of stoker are, of course, much worse than others, the ordinary chain grate being apt to be very bad. Various American authorities, e.g. W. C. Wilcox of the American Chemical Society, give the average figure of unburnt fuel in the ash and clinker with "overfeed" stokers as about 25 per cent, corresponding to 4½ per cent of the coal bill, whilst for chain-grate stokers the figure is 35 per cent unburnt carbon and about 6 per cent of the coal bill. The figures for hand-firing on small boilers are said to be even worse, viz. over 35 per cent unburnt carbon and about 6½ per cent loss in the coal bill. Further authentic data on this point are certainly required, and in this connection a paper read in September last by W. S. Patterson before the Yorkshire Section of the Society of Chemical Industry * is of interest. Detailed results of investigations carried out on the composition of the ash and clinker from 15 different mechanical-stoker plants are given, and the amount of carbon in the ash was found to vary from 5·2 per cent to 40·48 per cent, corresponding to 0·75–19·10 per cent of the original carbon in the coal. It should be noted, however, that out of the 15 plants 9 had over 15 per cent of unburnt carbon in the ash, and 12 plants had over 2 per cent of the original carbon of the coal in the ash, whilst 10 plants had over 3 per cent and 6 plants over 5 per cent.

It may also be pointed out that special plant has been developed extensively in Germany for the magnetic separation of ash and clinker from unburnt fuel, and one firm is stated to have supplied over 100 plants treating about 8 000 tons of ashes per day. The result of this very extensive experience is that the average unburnt fuel in ash and clinker exceeds 30 per cent and is in some cases actually over 50 per cent. What the figure is on the most modern type of mechanically-fired plant is not clear, but at any rate we may take a figure of 2 per cent loss on the coal bill as being the best stoker practice.

That is to say, with pulverized coal there is a saving due to less combustible in the ash of about 1·25 per cent in the coal bill in the case of the best stoker practice, and probably about 3–4 per cent with the ordinary present practice in, say, over 90 per cent of power stations.

(3) *Flexibility as regards the qualities of fuel that can be burnt.*—The great advantages claimed in the past for pulverized fuel in this respect have been more than substantiated by the experience at a number of installations in addition to that at Lakeside, and, in fact, almost a revolution has been effected in steam generation on this account alone.

Mechanical stokers are largely dependent—within very fine limits—on coal of good quality in order to obtain the most efficient results, that is to say, not only as regards the heating value, but other qualities as well, such as variation in the melting point and the amount of the ash, and the coking properties, i.e. the proportion of resinous matter in the coal. It is, of course, common knowledge that if a mechanically-fired plant is running at 75 per cent efficiency with coal of, say, 12 000 B.Th.U.'s per lb., any very great variation in the quality, such as a reduction to 9 000 B.Th.U.'s, would simply throw the whole plant entirely

* See *Chemistry and Industry*, 1923, vol. 42, p. 904.

out of gear, reduce the efficiency to, say, 65 per cent and cut down the evaporation by half, whilst the installation would very soon be congested with clinker. In other words, with mechanical stoking we are compelled to consider the performance of a boiler plant not so much from the point of view of the heat given to the furnace, but of the weight of a given coal possessing a number of distinctive qualities—quite another proposition.

With pulverized fuel the matter is altogether so different as to alter the whole method of regarding a boiler. Thus, if all qualities of coal are used, there is practically no difference in the efficiency or the steam output of the boiler. A drop to 9 000 B.Th.U.'s from 12 000 B.Th.U.'s merely requires some extra pulverized coal to be added to the combustion chamber, and the performance carries on as before. That is to say, with pulverized fuel all that is necessary is to apply to the boiler a definite amount of heat, and the weight and quality of the coal or other fuels are minor matters to be altered accordingly only so far as is necessary to keep the heat supply constant. Thus one of the chief reasons why the Detroit Edison Co. have finally decided to install pulverized fuel, after the most elaborate investigations into its possibilities, on a 300 000-kW installation is the advantage of being able to burn fuel of greatly varying quality with comparatively little reduction in the highest efficiency figures. Another reason is that with a given boiler one-third more capacity is available at any time. Pulverized fuel was also adopted for the Cahokia station, St. Louis, largely on this account, and, as further illustrating the advantages in this respect, mention may be made of the United Railways installation at Providence, Rhode Island, U.S.A., of 3 Bigelow-Hornsby boilers each of 174 000 lb. evaporation from and at 212° F., arranged to burn either good-grade bituminous coal or purely refuse anthracite coal, not hitherto burnt at all. The plant is specially adopted for this dual capacity, so that the bituminous coal guarantee is lower than usual, viz. 81·5 per cent efficiency on a normal evaporation of 10·5 lb. per sq. ft. of heating surface per hour, and 79 per cent on a 2-hour peak load of 13·8 lb. of water per sq. ft. of heating surface. The Rhode Island anthracite coal is extraordinarily difficult to burn, being of a graphitic character which burns well for a short time and then goes out, due to the ash preventing the inner portions from burning; as a consequence it is a waste product in spite of its high heating value. A similar anthracite fuel is found in the Alps, Belgium and Rumania, and important developments may result in this direction.

(4) *Combined working with liquid and gaseous fuels.*—The fact that pulverized fuel will give more efficient results either by itself or mixed separately with any gaseous or liquid fuel, or with both together, is in practice also a very important advantage. Thus it has made possible for the first time, at the River Rouge plant of the Ford Motor Co. at Detroit, a solution of the difficult problem of burning huge volumes of blast-furnace gas, erratic in delivery, along with coal so as to maintain a reasonably steady output of steam.

It is the present custom in many steel-works to burn the blast-furnace gas under a range of boilers, and solid coal in an adjoining range of boilers, whilst coal is also often burnt under the gas-fired boilers as well.

The results are almost always deplorable from the point of view of economical working. Thus in one large steel-works boiler plant tested by the author, an enormous amount of coal, over 60 000 tons per annum, was being burnt at about 50 per cent efficiency, using both water-tube and cylindrical boilers, in an endeavour to cope with a variable steam demand from rolling-engines and a widely fluctuating blast-furnace gas supply. Pulverized fuel used under such conditions would save something like 40 per cent of the coal bill, an almost incredible figure, which is also on the assumption that the efficiency of the blast-furnace gas-firing was not increased.

The River Rouge plant is, of course, the classic example of the advantages of pulverized fuel with respect to the burning of mixed fuels. The normal working conditions on this plant, with the present installation of 4 boilers (3 working), are 70 per cent blast-furnace gas and 30 per cent pulverized fuel, each boiler having 26 470 sq. ft. heating surface (2 650 American horse-power rating), running easily at an evaporation of 200 000 lb. of water from and at 212° F. each per hour (250 per cent American rating), at 235 lb. pressure and 600 deg. F. superheat. The usual fuel consumption per 24 hours under these conditions is 67 000 000 cubic feet of blast-furnace gas at a pressure of 1½ in. of water, a temperature of 300° F., and having a heating value of 100 B.Th.U.'s per cubic foot (at normal temperature and pressure) together with about 275 tons of pulverized coal, 94 per cent through 100 mesh and 78 per cent through 200 mesh, being therefore finer than usual. Any proportion of blast-furnace gas and pulverized coal can, however, be burnt as required, and alterations can almost simultaneously be made in the relative amounts of the two fuels, the gas being introduced horizontally into the bottom part of the furnace through grids. Thus, not only is pulverized coal alone often used, but, as required, varying quantities of coal tar from the by-product plant and coke-oven gas, whilst during the recent American coal strike oil fuel and coke breeze were also utilized.

(5) *Overload and flexibility in steam output.*—The flexibility of pulverized fuel from the point of view of overload and steam output on the plant is found to be, at the Lakeside and other plants, much greater than was imagined. Thus a boiler can, in a comparatively short time, be put on to full load from a "banked" condition, i.e. under pressure but with no combustion at all, thus differing, of course, from banking up with mechanical stoking.

As an example of the remarkable possibilities in this respect, one of the boilers at the River Rouge plant, because two other boilers were shut down for a short time on account of some boiler feed-pump trouble, rapidly increased the evaporation until, at the end of 30 minutes, the figure was 350 000 lb. from and at 212° F., the normal figure being about 200 000 lb. Mr. Bowden, the Chief Engineer of the Poplar Borough Council Electricity Works, who has recently visited a number of pulverized-fuel power stations in the United

States, told the author that he saw one of the River Rouge boilers started up after standing for several hours, and in 15 minutes the evaporation was 230 000 lb. per hour. This flexibility of pulverized fuel as regards steam output seems to be the chief reason why such enormous boiler units are now being adopted in America. As already stated, boilers of over 30 000 sq. ft. heating surface, much more than twice the size of anything in Great Britain, are now under construction, and there is every possibility in the immediate future of boilers having a normal evaporation of 400 000 lb. being erected so as to enable one boiler and one 35 000-kW turbine to be worked as an entirely self-contained and independent unit. So far as the author is aware, there is no boiler having a normal evaporation of over 150 000 lb. per hour working with mechanical stokers, and the above enormous units are only made possible by pulverized fuel. With a combustion chamber of ample volume and sufficient area in the fuel feed-pipe there appears to be hardly any limit to the output possible.

(6) *Reduced stand-by and banking losses.*—The great flexibility in the evaporation means also a very considerable reduction—and, in fact, an almost entire elimination—of the stand-by and banking losses. Several of the largest plants in the United States have adopted pulverized fuel largely because of this factor.

If a boiler plant is subject to very considerable fluctuations in the steam demand and has long periods of banking up, then pulverized fuel is said to possess an advantage over mechanical stoking corresponding to a saving of as much as 2–5 per cent in the coal bill.

(7) *Ease of scientific control.*—The extraordinary ease with which pulverized fuel may be conveyed through pipes, being handled and controlled almost as readily as gas, means that an extremely accurate control of the working of a boiler plant is possible, especially since practically the whole of the air used is similarly under control and passed through pipes. The most remarkable developments in this direction have recently been made in America, partly at Lakeside but particularly at the River Rouge plant at Detroit.

In the latter installation each of the four very large boilers is fitted with a separate 3-panel control switchboard, one for each boiler, in a control room remote from the boiler house. These switchboards are each provided in the first place with recording pyrometers, one giving a chart of the temperature of combustion within the tubes of the boiler, at the exit gas discharge from the boiler, and in the chimney base, together with the steam temperatures, and with draught gauges for a number of different parts of the boiler plant. The battery of instruments on each board also includes steam and air meters, CO_2 recorder, steam pressure-gauge and superheat gauge, and special apparatus giving a continuous record of the rate of flow of the feed water, pulverized coal and blast-furnace gas. The board is further equipped with a series of switches controlling the pulverized fuel, air, and blast-furnace gas supply. In practice an operator stands in front of the board and, by merely manipulating switches, controls almost the entire working of the boiler, keeping it at the highest efficiency at different rates of evaporation, as required. There is also one attendant in front of each boiler, but he has practically nothing to do except in case of emergency, and the boiler house contains more men cleaning and polishing than looking after the boilers.

Such ultra-scientific methods are only possible with pulverized fuel because of the ease of control, and it is understood that, with the four new boilers now being erected, there will be one instrument board only and one operator to control the working of a plant capable of evaporating over 800 000 lb. of water from and at 212° F. per hour, a normal long-period overload being 225 000 lb. of water per boiler per hour. In an emergency, over 1 000 000 lb. of water per hour can be handled on the plant for long periods.

The normal winter load on this present plant is 13 000 000 lb. of steam per day, i.e. about 8·5 lb. of water from and at 212° F. per sq. ft. of heating surface per hour, but 14·5 lb. can be taken as an overload. All the make-up is pure distilled water, of which on the average 1 380 tons per day is used, the evaporator room being 350 ft. long by 60 ft. wide, containing a double row of 9 evaporators connected in parallel, the heating being obtained by steam coils. As a consequence, since scale is eliminated and as the pulverized-fuel plant is absolutely reliable, these boilers are normally run for six months continuously and have often been in operation for nine months, whilst there will be no maintenance cost for three years. The present plant, as already stated, consists of 4 boilers of 26 500 sq. ft. heating surface, each unit being entirely independent with its own superheater and steel chimney, boiler-feed circuit, control panel, etc. The boilers are of the Ladd type having five drums, viz. four steam and water drums and one top steam-collecting drum. The boiler house containing the 4 boilers is 350 ft. long by 225 ft. wide, the roof being 120 ft. from the ground. The four steel chimneys are each 327 ft. high above the ash-level floor and 11 ft. internal diameter. The boiler house is divided into four main floor-levels, in addition to intermediate gangways. The top floor is the conveyer floor, to which the pulverized coal is brought from the adjacent pulverizer house by means of spiral conveyers and delivered to the pulverized-coal bunkers underneath, these bunkers having a capacity of 1 100 tons or about 4 days' supply. At a distance of 65 ft. below this level is the boiler-operating floor, whilst the next stage is the steam-pipe gallery floor, and finally the ash-level or ground floor. In each case the complete unit of the boiler, superheater setting, and steel chimney, weighing about 1 000 tons, is hung bodily on the structural steelwork of the building. The total height of the boilers from the ash-pit floor to the top of the superheater steam piping is 82 ft. 9 in. and the floor space of each boiler is 29 ft. by 31 ft.

The combustion chamber is approximately 23 ft. by 24 ft., and 55 ft. high, corresponding to a combustion volume of 5 cubic feet per rated American horse-power, whilst the pulverized plant has a capacity of 750 tons of coal per 24 hours, the pulverizer building being 200 ft. long, 60 ft. wide and 109 ft. high. It is estimated that the total cost of the River Rouge power plant and its subsidiary generating, transforming and dis-

TABLE 9.

(A) Boiler House.

Total tons (American) of coal consumed = 15 311, equivalent to 13 670 tons (English).

Class of labour	Number of men	Hours	Rates	Amount	Total	Cost per ton of coal consumed
			$	$	$	cents
First assistant engineer	1	115		98·81		
Boiler room engineer	1	260·5		212·50		
Watch engineer	1	76		44·00		
Ditto	1	75		47·50		
Ditto	1	76		44·00		
Boiler room assistant engineers ..	3	523		418·75		
Total	8	1 125·5	0·770 (av.)		865·56	5·66
Furnace operator	1	224	0·72	161·28		
Ditto	1	24	0·71	17·04		
Ditto	1	247	0·74	182·78		
Ditto	1	243	0·68	165·24		
Ditto	2	472	0·69	325·68		
Ditto	1	247	0·60	148·20		
Ditto	1	116	0·58	67·28		
Total	8	1 573	0·678 (av.)		1 067·50	6·97
Instrument man	1	197	0·69	135·93	135·93	0·83
Boiler feed pumpman	1	240	0·58	139·20		
Ditto	1	229	0·67	153·43		
Ditto	1	235	0·74	173·90		
Total	4	901	0·663 (av.)		466·53	3·04
Oiler, feeder drives, etc.	1	178	0·43	76·54		
Ditto	1	173	0·61	105·53		
Ditto	1	63	0·67	42·21		
Total	3	414	0·542 (av.)		224·28	1·46
Boiler room helper	1	108	0·47	50·76		
Ditto	1	220	0·45	99·00		
Ditto	1	131	0·43	56·33		
Ditto	1	132	0·43	56·76		
Total	4	591	0·445 (av.)		262·85	1·72
Ashman	Total of 17 men	81	0·63	51·03		
Ditto		152	0·61	92·72		
Ditto		772	0·43	331·96		
Total	17	1 005	0·474 (av.)		475·71	3·11
Miscellaneous labour such as cleaning boiler plates, blowing tubes, sweeping, etc.	Total of 19 men	319	0·63	200·97		
		520	0·61	317·20		
		50	0·67	33·50		
		7	0·45	3·15		
		482	0·43	207·26		
Total	19	1 378	0·554 (av.)	—	762·08	4·96
Boiler room total	63	6 987·5	0·610 (av.)	—	4 260·44	27·75

TABLE 9—*continued.*

(*B*) *Pulverizing House.*

Total tons (American) of coal consumed = 15 311, equivalent to 13 670 tons (English).

Class of labour	Number of men	Hours	Rates	Amount	Total	Cost per ton of coal consumed
			$	$	$	cents
Mill room foreman	1	234·5	0·80	187·50	187·50	1·22
Operation and maintenance man ..	1	176	0·73	128·48		
Ditto ..	1	150·5	0·67	100·84		
Ditto ..	1	114	0·65	74·10		
Total	3	440·5	0·688 (av.)		303·42	1·98
Mill operator	1	223·5	0·66	147·51		
Ditto	1	230·5	0·65	149·83		
Ditto	1	224·0	0·70	156·80		
Total	3	678·0	0·670 (av.)		454·14	2·96
Drier operator	1	208	0·64	133·12		
Ditto	1	224	0·58	129·92		
Total	2	432	0·608 (av.)		263·04	1·72
Fuller-Kinyon pumpman	1	234	0·60	140·40		
Ditto	2	445	0·58	258·10		
Total	3	679	0·587 (av.)		398·50	2·60
Bin man	1	204	0·60	122·40		
Ditto	1	150	0·63	94·50		
Ditto	1	238	0·56	133·28		
Total	3	592	0·592 (av.)		350·18	2·29
Relief man	1	170·5	0·63	107·42	107·42	0·70
Conveyer man, pulverizing house ..	1	96	0·61	58·56		
Ditto ..	1	216	0·56	120·96		
Ditto ..	1	207	0·58	120·06		
Total	3	519	0·578 (av.)		299·58	1·96
Crusher, shaker, inclined conveyer, operating, cleaning and oiling	1	209	0·64	133·76		
	1	202	0·65	127·26		
	1	186·5	0·60	111·90		
	1	224	0·64	143·36		
Total	4	821·5	0·629 (av.)		516·28	3·37
Pulverizing house: Total	23	4 567·0	0·631 (av.)		2 880·06	18·80
Total for complete boiler plant.						
Boiler room	63	6 987·5	0·610 (av.)		4 260·44	27·83
Pulverizing house	23	4 567·0	0·631 (av.)		2 880·06	18·80
Grand Total	86	11 554·5	0·618 (av.)	—	7 140·50	46·63

tributing station is very nearly $10 000 000, and the present extensions, including the duplicating of the boiler plant, will cost another $6 000 000. The Ford works employ about 40 000 people and turn out normally 5 000 cars and 500 tractors per day. One of the problems is to handle the private cars of the employees, which are parked in acres of ground, and the works include 300 miles of railway, which is to be electrified by the Ford staff. It is, therefore, rather a striking commentary that the Ford Co. should have adopted pulverized fuel, and also be at present doubling the plant. For reasons of this kind, therefore, it is very difficult to give a really fair comparison as regard net efficiency, since the control with pulverized fuel is infinitely easier than mechanical stoking, a substantial advantage not possible to express in figures.

(8) *Labour costs.*—The net result of long experience at the Lakeside station is that the total labour and staff costs are about $0·465 per American ton (2 000 lb.), corresponding to 25d. per English ton (2 240 lb.) on the basis of American wages and conditions. The average rate of wages in Milwaukee (1922) was $0·620 (2s. 7d.) per hour, so that in Great Britain, where the wages are less than half, the total labour cost would be about 1s. 2d. per ton, whilst the corresponding figure in Great Britain for mechanical stoking is at least 20 per cent higher.

The detailed labour figures at Lakeside for a typical month (April 1922) for the complete boiler installation, divided into (A) boiler house, and (B) pulverizer house, are given in Table 9.

The total staff in the boiler house is 63 men at a total wage of $4 260·44, equivalent to, say, £852 per month, corresponding to a total cost of 27·63 cents per American ton (2 000 lb.), or 15d. per English ton (2 240 lb.) on the basis of American wages.

The total staff for the complete boiler house, boilers and pulverizing plant together, is 86 men at a total wage of $7 140·50, equivalent to, say, £1 428·1 per month, corresponding to a total cost of $0·465 per American ton or 25d. per English ton on the basis of American wages.

As already stated, the average wage in Milwaukee in 1922 was $0·620 (2s. 7d.) per hour. This is, however, more than double the wage in Great Britain, so that the British wage cost per ton is about 1s. 2d.

The exact labour costs of another large modern pulverized-coal installation of 3 000 h.p. described in a recent report by H. Kreisinger will also be of interest in this connection. The figures given are for 12 months' running, including all stoppages, during which 43 703 (American) tons of coal were burnt in the pulverized condition. As already stated, the total labour costs were $23 680·52 per annum, corresponding to $0·542 per ton, and for a given month of continuous running the labour figures for unloading, crushing, pulverizing, drying, boiler washing, and ash handling, for the burning of 3 150 tons, are given in Table 10.

TABLE 10.

Labour Costs for One Month's Continuous Running with Pulverized Fuel.

	Hours	Rate	Cost per month
		cents	$
Unloading cars to track hopper pulverizer	622	40	248·80
Pulverizer mill operator (day)	208	60	124·80
Pulverizer mill operator helper (day)	208	40	83·20
Pulverizer mill operator (night)	208	50	104·00
Pulverizer mill operator helper (day)	208	40	83·20
Fireman	720	51	367·20
Boiler washer and cleaner	416	40	166·40
Repair man, acting foreman of washer and cleaner ..	208	60	124·80
Ash handler	208	40	83·20
Total			$1 385·60 (= $0·439 per ton)

In the first place these figures confirm in a striking manner those given previously by various American advocates of pulverized fuel, for example by Mr. N. C. Harrison, already mentioned. Again, Scheffler and Barnhurst stated that, as a typical example with a plant of 100 tons per 24 hours and wages at $0·400 per hour, it would take 34 labour-hours to prepare the fuel and deliver it to the conveyers, at a cost of $0·140 per ton. At Lakeside, a plant of 650 tons per 24 hours with labour at $0·620 per hour in 1918, the figure was 18·80 cents (9·50d.).

It is particularly difficult also to give fair average general figures for labour costs, because these decrease at a rapid rate as the size of the plant increases, and the rate of wages varies considerably. Thus it is stated that at $0·400 per hour, for a plant of 1 000 tons per 24 hours, the labour costs in preparing the fuel would only be 115 labour-hours or $0·04 (2d.) per ton. With an extremely large plant of 5 000 tons

per 24 hours this would be further cut down to \$0·025 (1·25d.) per hour.

The same difficulties apply, of course, to mechanical stoking. The actual detailed figure at Dalmarnock for 14 months, with a total of 78 men employed, was approximately 19·0d. per ton at 34 per cent load factor. Under better conditions of output this figure would, of course, be somewhat improved, but based on these comparative figures and the opinion of many American engineers it can be stated that, at any rate for a large plant of, say, 40 000 kW, and with scientific supervision, pulverized fuel is lower in labour costs to the extent of something like 20 per cent.

(9) *Amount of power consumed in the preparation of the fuel.*—The net result of many months' records at Lakeside covering the preparation and consumption of nearly 500 000 tons of pulverized fuel since the station opened, is that the total auxiliary power used for handling, crushing, drying and pulverizing the fuel, including that used for lighting and other incidentals, is equivalent to 2·13 per cent of the steam production of the plant, the preparation of the pulverized fuel accounting for only 1·75 per cent, which figure has now, however, in the case of the Lopulco system, generally been reduced by the new vertical drying, using merely the waste-heat gases. The net figure is about 1 per cent of the steam production of the plant, equivalent to about 19½ kW. per ton of coal. As previously pointed out, these are also the actual guarantee figures for Vitry.

The figures at Lakeside are well illustrated in Table 11, which gives the exact cost of light and power in the pulverizing building, with the output of dried and pulverized coal, together with the cost of pulverizing per ton, for four separate months (February to May, inclusive) in 1922.

Taking a typical month, that of May 1922, the exact amount of power used in the station, as recorded by a battery of meters, is shown in Table 12, the total number of units generated being 20 299 000.

It will be seen, therefore, that the total auxiliary power for all sources on the entire Lakeside station, including, of course, the turbine plant, amounts to 3·97 per cent of the power generated. Of this amount, however, only 1·75 per cent is used for the actual preparation of the pulverized fuel, and 0·38 per cent for boiler-house auxiliaries, such as handling the fine ash, lighting, etc., i.e. 2·13 per cent for steam generation.

It should also be mentioned that the pulverizing plant can in practice be run almost entirely at night when the load on the station is light, thus storing up fuel for the heavy day loads, so that with a little care in management the real net cost of the power used is extremely small, as of course the light-load losses of the stations are in any case continuous, and the value of the actual power used is practically nil. However, for the purpose of argument we can take the power at its full value, that is as if deducted from the day load available for sale.

With regard to drying, as previously stated, the rotary driers at Lakeside take the equivalent of about 1 per cent of the steam generated, but these are already obsolete. The new vertical driers, using 10 per cent of the waste chimney-gases, require merely 3 kW per ton of coal for the fans to maintain the drying current of mixed hot gases and air through the drier.

Some interesting facts have been brought to light as the result of the extensive experience obtained concerning the drying of coal and the amount of moisture that can be left in. It is now known, for example, that the difficulties of drying are chiefly caused by the extraneous or added moisture and not so much by the natural moisture. For example, if a coal at the pit face contains in its natural state 3–4 per cent of moisture it is not necessary to dry it down to 2 per cent of moisture, as in the case of a pulverizer coal-fired boiler plant near the pit-head. If, however, the coal contained, say, 1 per cent of moisture and 3 per cent of moisture was added due to exposure to the weather, then this coal would not work efficiently in the process and it would be necessary to dry it down to 2 per cent. Most coal, of course, contains 6–10 per cent of moisture, but a large part of this is extraneous moisture.

It can be taken as authentic that the auxiliary power consumption of a large, modern, pulverized-fuel installation for all practical purposes is a maximum of 19½ kW per ton, equal to, say, 1 per cent of the steam production of the plant, divided, in the case of the Lopulco system, as follows:—

Pulverizing mills	.. .. ..	12·0 kW
Conveyers	.. ..	1·0 ,,
Vertical driers	.. .. ..	2·7 ,,
Fans	.. ..	3·0 ,,
Pulverized-coal feeds	.. ..	0·8 ,,
Total	.. .. ..	19·5 kW

TABLE 11.

Cost of Power used in the Pulverizing Building at Lakeside, Milwaukee. (American ton = 2 000 lb.).

Month	Lighting	Power	Total units	Coal used	Units per ton	Cost per ton at 0·6 cent per kWh
	kWh	kWh	kWh	tons	kWh	cents
February	13 220	314 470	327 690	14 118	23·2	11·60
March	14 324	366 376	380 700	15 996	23·7	11·85
April	13 192	377 667	391 579	15 311	25·5	12·75
May	8 114	370 684	378 798	15 708	24·0	12·00

As regards mechanical stoking, it is, as usual, difficult to obtain authentic figures. The different methods by which auxiliary steam or power may be taken by a mechanically-fired water-tube boiler plant are given in Table 13, together with what may be considered to be average figures for the equivalent steam production.

Several of the items, viz. 5, 6 and 8, are common to both systems of firing, and of course many plants are not equipped with items 7, 8 and 9, and, as previously stated, the latest type of mechanical stoker requires less than 1 per cent for items 3 and 4 together. stations to this question of auxiliary power. In many industrial plants the figures are most unsatisfactory, often over 10 per cent of the steam generated being lost in the firehole.

In general, therefore, pulverized fuel certainly results in no more auxiliary power being used than in mechanical stoking, and many of the previous ideas held on this question were quite erroneous.

(10) *Maintenance costs.*—With regard to maintenance costs, wear and tear and breakdowns in the preparation plant, damage to the firebrick linings and settings, and damage to the boiler, the experience at Lakeside, after nearly 3 years' running, is that the ideas of many engineers as to the excessive cost of these items for a modern plant have not the slightest foundation in fact. Thus the total cost of repairs to the pulverizers has been less than 1¼d. per ton, and it is claimed that the maintenance costs, particularly of the brickwork, are less than with mechanical stoking.

TABLE 12.

Total Actual Electrical Energy used at Lakeside as recorded by Meters. May 1922.

Output of station = 20 299 000 kWh generated (gross).

	440 volt	250 volt	Total	Percentage of turbine room units	Percentage of total station units	Percentage of total units generated
	kWh	kWh	kWh	per cent	per cent	per cent
Turbine Room.						
Turbine room lighting	5 933	979	6 912	1·87	0·86	0·03
Turbine room auxiliaries	361 440	—	361 440	98·13	44·81	1·78
Emergency exciter No. 1	—	2	2	—	—	—
Emergency exciter No. 2	—	—	—	—	—	—
Total turbine room power	367 373	981	368 354	100·00	45·67	1·81
Boiler House.						
Boiler house lighting	5 934	489	6 423	8·43	0·80	0·04
Boiler house auxiliaries	69 760	—	69 760	91·57	8·65	0·34
Total boiler house power	75 694	489	76 183	100·00	9·45	—
Pulverizer Building.						
Pulverizer building lighting	5 933	629	6 562	1·84	0·81	0·03
Pulverizer mills, driers, pumps, screw conveyers, drier feed motors	344 380	5 207	349 587	98·16	43·34	1·72
Total pulverizer building power	350 313	5 836	356 149	100·00	44·15	1·75
Shaker-hammer-mill crusher, 48-in., inclined belt	5 670	228	5 898	—	0·73	0·03
Total pulverizing power	—	—	362 047	—	44·88	1·78
Station total	799 050	7 534	806 584	—	100·00	3·97

As far as Dalmarnock (a typical, modern mechanical-stoker station) is concerned, the amount of auxiliary power for coal and ash handling, mechanical stoker, mechanism, mechanical draught, etc., was 1·68 per cent of the steam production of the plant, that is to say 0·45 less than that used at Milwaukee, or about 0·55 more than in the case of pulverized fuel with the modern vertical drier. Probably the average figure for British power station practice is 2–3 per cent of the steam production, inclusive of all the auxiliaries, although in many cases the figure is well over 3 per cent, and nothing like sufficient importance is attached in power

The actual figures at Lakeside as regards the pulverizing plant are as follows, taking the results of 15 months' continuous running, viz. March 1921 to May 1922 inclusive, during which period 183 046 American tons

(of 2 000 lb.) [equal to 163 430 English tons (of 2 240 lb.)] of coal were pulverized. The repairs, of which the most detailed record was kept, included the following number of balls replaced in the pulverizers:—

Mill No. 1	12 balls
Mill No. 2	17 ,,
Mill No. 3	13 ,,
Mill No. 4	12 ,,
Mill No. 5	16 ,,
Mill No. 6	6 ,,
Mill No. 7	9 ,,
Mill No. 8	4 ,,
Total	89 balls

The price of these balls is \$16·25 each, so that the total cost is \$1 446·25, say about 0·40d. per ton of coal for pulverizer ball replacement.

TABLE 13.

Mechanical Stoking.

Source of auxiliary steam or power used	Average steam or power consumption, expressed as percentage evaporation of the plant
(1) Coal conveyers	0·50
(2) Ash conveyers	0·25
(3) Mechanical stoker mechanism ..	0·50
(4) Mechanical draught	1·50
(5) Boiler feed pump	1·00
(6) Water - softening plant and accessories	0·50
(7) Economizer scrapers (with cast-iron tubes)	0·10
(8) Electrolytic corrosion treatment	0·50
(9) Soot cleaners, and other minor uses	0·01
Total	4·86 per cent

There were also replaced during the period October 1921 to May 1922 inclusive (8 months) two rings, one in No. 1 mill and one in No. 2 mill, at \$420 each, equal to a total of \$840, and during this period 115 630 American tons (of 2 000 lb.), equivalent to 103 240 English tons (of 2 240 lb.), were pulverized, the cost per ton for new rings therefore being 0·39d. Finally, from March 1921 to May 1922 inclusive (15 months), when, as already stated, 183 046 American tons (of 2 000 lb.), equivalent to 163 430 English tons (of 2 240 lb.), were pulverized, two new sets of drive gears were required, one for No. 1 mill and one for No. 4 mill, costing \$651 per set, a total of \$1 302, corresponding to about 0·38d. per ton of coal. The total cost, therefore, of repairs to the pulverizing plant for over 12 months' running is about 1·17d. per ton.

As showing the steady running of the pulverizers, Table 14 gives the output figure for 7 months.

With regard to the brickwork, it is strongly claimed by Mr. Anderson, as a result of a detailed experience of over two years at Lakeside, that the wear and tear on the modern type of brickwork is now less with pulverized fuel than with mechanical stoking, chiefly because of the water screens and the hollow air-cooled furnace walls.

This conclusive experience at Lakeside confirms the previous experience on other plants that under proper conditions—which there is no difficulty in attaining—pulverized fuel actually costs less in maintenance charges than mechanical stoking.

Scheffler and Barnhurst maintained in their paper of 1919 that pulverized coal is less liable than mechanical stoking to cause breakdowns and excessive wear and tear, because nearly all the mechanism is outside the furnace, whilst the Allegheny Steel Co., for example, have run boilers on Lopulco pulverized fuel for four years with only trifling repairs. Also the Lima locomotive works in Ohio ran 3½ years and the Oneida-street plant a similar period before the settings were rebuilt. There is no sign of damage to the boilers, and this is purely an exaggeration so far as modern installations are concerned.

TABLE 14.

Output of Pulverizing Mills for the Months November 1921 to May 1922 inclusive.

	Tons	Hours run	Tons per hour
November 1921..	13 564·55	3 213·25	4·22
December 1921..	11 576·90	2 499·92	4·63
January 1922 ..	14 910·50	2 776·50	5·36
February 1922 ..	14 118·25	2 016·25	7·00
March 1922 ..	15 995·66	2 239·50	7·14
April 1922 ..	15 311·19	2 419·25	6·33
May 1922 ..	15 706·50	2 481·25	6·33
Total ..	101 183·55	17 645·92	5·73 (av.)

The results at Milwaukee therefore show that the opinions often held, especially in Great Britain, that pulverized fuel causes excessive wear and tear and depreciation, together with continual repairs and costly breakdowns, are entirely erroneous. On the contrary, pulverizing mills have ground millions of tons of coal at only a trifling expense for repairs, and the costs of setting and brickwork are, as already stated, now claimed to be less than with mechanical stoking, always providing, of course, that both methods of control and the equipment are on modern lines.

Mr. Anderson gives it as his opinion that pulverized fuel has the advantage from the wear-and-tear point of view in that no ironwork—except the actual burners—is near the heat, and it is a striking commentary that the Lopulco guarantees are now stated to cover three years' life for the brickwork, a period for which no mechanical-stoker firm could give a guarantee with ordinary solid furnace walls.

There is no question also that a careful consideration of

the most modern American pulverized-fuel installation shows a smaller percentage of stand-by plant than in the case of mechanical stoking. Thus at the River Rouge plant of four boilers, three are working regularly and often four, and at the Trenton Channel station one boiler will be a stand-by, out of six. On very large boilers it is impossible to work mechanical stokers continuously as can be done with pulverized fuel, and a breakdown of a large stoker (which occasionally happens) is apt to be a very serious matter. To-day, of course, the tendency is practically to eliminate boiler breakdowns by the use of only pure distilled water for the make-up as well as for the main supply. At the Ford plant, as already stated, the boilers are run for 6–9 months without a stop. This is easily possible with distilled water and pulverized coal, but not with distilled water and mechanical stoking, because the latter is now more liable to breakdown, the best mechanical-stoker figures being 90 days, at Colfax.

fuel to the extent of over 3 000 000 tons per annum for steam generation, some of the largest and most efficiently managed power plants in America being concerned.

It is, of course, agreed that reasonable precautions must be taken. Thus all bins, conveyers, storage hoppers, driers and pulverizers are required to be dust-tight, and no wood must be used in the buildings, which have to be kept absolutely clean and free from coal dust.

This, however, is easily accomplished by means of vacuum cleaners, and various modifications in the design of the buildings have been introduced; for example, all the spars and girders are arranged so that dust cannot lodge on them and fall down in a shower.

Again, in a modern installation the pulverized fuel is only mixed with any considerable quantity of air immediately at the burner. Pulverized fuel itself in bulk is not particularly dangerous, but only when mixed with sufficient air in the form of a cloud.

TABLE 15.

Figures given by Scheffler and Barnhurst for the Cost of Preparation of Pulverized Fuel, per ton.

	100-ton-per-24-hour plant	1 000-ton-per-24-hour plant
	$	$
Power: 17 kWh per ton net, at 0·75 cent per kWh	0·1275	0·1275
Labour: 40 cents per hour	0·1400	0·0400
Coal for drying, at $5 per ton delivered	0·0600	0·0600
Repairs	0·0700	0·0700
Total cost of pulverizing	0·3975	0·2975
Interest at 6 per cent	0·1050	0·0390
Depreciation	0·1200	0·0400
Taxes and insurance	0·0350	0·0130
Total net cost per American ton (2 000 lb.)	$0·6575	$0·3895

As usual, it is very difficult to get corresponding detailed cost figures for mechanical stoking, but the maintenance is obviously greater than with pulverized fuel, even under the most modern conditions. In both systems the number of crushers and coal conveyers will be about equal, together with the fans and trunking, and the repairs to the brickwork and settings are less for pulverized fuel. The repairs to the average mechanical stoker mechanism are apt to be very heavy under ordinary conditions, and in the case of cylindrical boilers sometimes simply ruinous, but the author has not sufficient authentic data to suggest an average figure for high-class stoker performance.

(11) *Danger of explosions and fires.*—It is generally agreed in America that this, whilst naturally more pronounced than in the case of mechanical stoking, is not now a serious matter. There has been no explosion in any modern plant, and no serious fires, and the possibility of danger will not prevent, as already seen, the adoption within the next few months of pulverized

It is interesting also to note that the horizontal revolving drier has been responsible for most of the fires that have occurred, especially the completely obsolete pattern in which hot gases from the auxiliary furnace passed through the coal itself. Thus the coal often became ignited and the flames passed back to the pulverizer. The later types of rotary drier, as used at Lakeside, are of the double-shell variety in which the flames and hot gases pass between an inner and outer shell and never come into contact with the coal passing inside the drier. This type resulted in a big reduction in fires, and the new vertical drier already described will practically eliminate these altogether since there is no longer any need for an external furnace.

(12) *Ash troubles.*—With regard to the question of fine ash being blown all over the inside of the boiler plant installation, in the first place the distribution of the ash at Lakeside is found to be such that 25–50 per cent of the ash falls to the bottom of the combustion

chamber, 25–35 per cent is caught in the chimney base, and 12–25 per cent is blown out of the top of the chimney. The idea that 50 per cent or over is discharged from the chimney is not correct, unless the plant is forced much above the normal evaporation.

Of course, in comparison with the early types of plant the use of a very large combustion volume combined with the zone system of design has meant the rapid slowing down of the pulverized-fuel current, so that a large proportion of the ash separates before the boiler tubes are reached and is thus deposited in the bottom of the furnace.

On the average about 17½ per cent of the ash seems to be discharged from the chimney top, but it is in the form of an excessively finely divided, flocculent powder. As already stated, about 65 per cent of the coal is pulverized sufficiently to pass through a 200-mesh screen, so that the resulting ash must be much smaller. There seems to be no question that the combustion of the coal is so rapid that the particles have not time to soften and stick together, so that, if the coal contains 10 per cent of ash, the diameter of the ash particles will be approximately 1/4 000 inch.

It is stated that modern pulverized-fuel installations in America give no trouble at all in this respect and that the 12–25 per cent of the ash is never seen again, even in the most crowded centres. It must also be remembered that quite a considerable amount of ash and partially burnt fuel already goes up the chimney where mechanical stoking is used. This is, in fact, an intolerable nuisance in some cases because of the short steel chimneys now so largely used and also because of the large size of the particles. In the author's opinion there ought to be included in a proper boiler-test code some method of determining this solid material in the chimney gases. In a recent careful test in the United States it was discovered that with mechanical stoking no less than the equivalent of 3 per cent of the coal fired was discharged from the chimney top. This is quite as much as with pulverized fuel, except that the latter has the advantage of being in the form of an impalpable powder.

It is, of course, possible that some day all chimneys will be required to prevent the emission of both black smoke and solid particles, so as to purify the air, but, generally speaking, pulverized fuel should not present any more difficulties in this respect than other methods of firing.

The trouble of slagging, as already pointed out, has been completely eliminated by the water screen, as shown also by the low cost of maintenance of the brickwork.

(13) *Capital costs.*—The author is unfortunately not in a position to give authentic figures for the comparative costs of mechanical stoking and pulverized fuel in Great Britain, in any case always a difficult matter to deal with in a general way, because of differences in the local conditions and the size of the plants. Taking, however, the erection of a new power station, as far as the author can ascertain the cost of a pulverized-fuel equipment (including coal-handling plant, coal crusher, conveyer to crushed coal bunkers, crushed

TABLE 16.

Revenue Expenditure at Dalmarnock.

Comparison costs for March 1923.

	Cost per unit delivered		
	Average for year	Preceding month	March 1923
Operation :—	d.	d.	d.
Coal	0·1654	0·1642	0·1643
Coal handling	0·0051	0·0051	0·0052
Ash handling	0·0038	0·0038	0·0033
Water	0·0008	0·0008	0·0009
Oil and stores	0·0019	0·0020	0·0017
Shift wages and salaries	0·0133	0·0124	0·0132
Maintenance and repairs :—			
Buildings : Wages ..	0·0036	0·0029	0·0049
Material ..	0·0012	0·0007	0·0014
Engine room : Wages ..	0·0072	0·0060	0·0086
Material	0·0018	0·0019	0·0019
Boiler room : Wages ..	0·0087	0·0090	0·0095
Material	0·0028	0·0022	0·0037
On-cost charges ..	0·0057	0·0055	0·0057
Totals	0·2213	0·2165	0·2243
Totals (less coal) ..	0·0559	0·0523	0·0600

Units :—	
Generated	17 116 800
Delivered	16 334 439
Coal consumed :—	
Tons	14 433
Lb. per unit delivered ..	1·98
B.Th.U.'s per unit delivered	19 943
Ashes removed :—	
Tons	2 068
Percentage to coal ..	14·33
Make-up water :—	
Gals. per unit delivered	0·044
No. of men employed :—	
Shift : Salaries	21
Wages	63
Time : Main. and repairs	87
Max. load at station ..	55 400
Load factor on station $= \left(\frac{\text{Units delivered}}{\text{Max. load} \times \text{hours}}\right)$	39·63
Total evaporation :—	
Lb. water per unit generated	204 604 630
Lb. water per lb. coal ..	6·328
Calorific value of coal, B.Th.U.'s	10 070
Boiler efficiency, per cent	77·9
Station efficiency (taken on units delivered), per cent	71·1

coal bunker, conveyer to drier, driers, conveyer to dried coal bunker, pulverizers, conveyers to pulverized-coal bins, coal feeders, burners, furnace equipment, and small steam ash-ejector), as compared with the same duty for a mechanical stoker equipment (coal-handling plant, very large overhead bunkers, trunking to stokers, mechanical stoker equipment and accessories, furnace equipment, and large ash conveyers), depends very largely on the size of the installation.

Very roughly, pulverized fuel costs more than mechanical stoking for comparatively small plants of, say, less than 6 000 kW, at 10 000 kW the difference is very slight, and over this there is no difference, whilst in the very largest plants pulverized coal is cheaper. Generally, however, there is not much difference as regards capital cost.

Most certainly the idea that pulverized fuel requires extensive stand-by plant is entirely wrong, and pulverizers, driers, burners, etc., do not break down or need any more reserve plant than mechanical stoking, each boiler now having a drier and pulverizer just as it has a mechanical-stoker equipment.

It may also be pointed out that in the case of the latest type of Lopulco installation such as at Vitry, the combined vertical gravity driers and pulverizers are placed on the boiler-house floor, and occupy very little more space than mechanical stokers and accessories, being quite different, from the point of view of buildings and foundations, from the old-fashioned central pulverizing plant and long rotary drier.

General Operating Figures.

The additional figures given below, being the total operating costs of pulverized fuel and mechanical stoking, will also be of interest after studying the Lakeside performance.

Scheffler and Barnhurst in their 1919 paper presented figures for the cost of preparation of pulverized fuel (see Table 15). These agree remarkably well with those at Lakeside, taking the different labour, coal and power costs into account.

The recent report by Henry Kreisinger, already mentioned in connection with labour costs, on the full details of the performance for 12 months' continuous running of a pulverized-fuel-fired boiler plant of 3 000 h.p., burning 43 750 tons of coal per annum is valuable, as giving the long period results on another large modern plant.

(1) Coal used, high grade Eastern (America) coal, bituminous screenings:—

Fixed carbon, per cent	48·3
Volatile matter	33·4
Ash	13·0
Moisture (as received)	5·2
B.Th.U.'s (as received)	11 771
B.Th.U.'s (dry basis)	12 414
(2) Coal burnt	43 703 tons (Am.)
(3) Water evaporated	854 158 170 lb.
(4) Water evaporated from and at 212° F. per lb. coal	9·75 lb.

(5) Total operating costs:—

(a) Coal	$224 709·39
(b) Repairs	7 216·00
(c) Supplies	7 271·88
(d) Water	13 330·30
(e) Labour	23 680·52
	$276 207·99
(6) Operating costs per 100 lb. steam	$0·324
(7) Total capital charges at 20 per cent	$52 799·66
(8) Total inclusive cost of operation	$329 007·65
(9) Net cost per 1 000 lb. steam	$0·385

In a given month the cost of labour, power, unloading, drying, pulverizing and conveying, exclusive of overhead charges, was $0·470 per ton.

Scheffler and Barnhurst give the following as average figures for the costs of operation of mechanical stokers in the United States, taking a large plant of 1 000 tons (American) of coal per 24 hours.

	$
Power for stoker, 2 per cent of the total boiler horse-power developed	180·00
Power for mechanical draught, 2 per cent of the boiler horse-power developed	180·00
Coal-handling: 100 kW at 0·75d. per kW	18·00
Labour for coal-handling: 2 men per shift (3 shifts) at 40 cents per hour	19·20
Repairs for stokers at 30 cents per boiler horse-power per annum	17·50
Repairs for coal-handling equipment	10·00
	$424·70

Total cost of operating, per ton: $0·425

Finally, the exact cost of Dalmarnock for an average 12 months' running and also for two typical months is given in Table 16, the average load factor on the station being 34 per cent, as already stated.

Conclusion.

The position with regard to pulverized-fuel firing for steam generation in comparison with mechanical stoking may therefore be summed up as follows:—

(1) *Efficiency.*—Under the best conditions pulverized fuel gives 86 per cent efficiency, and mechanical stoking 81½ per cent, representing 5½ per cent saving in the yearly coal bill. Pulverized fuel is, however, much easier to work in obtaining these figures, and under ordinary conditions the saving is 9–10 per cent, and in most existing stations would be 15–20 per cent.

(2) *Unburnt fuel in the ash.*—With pulverized fuel the figure is 0·40–0·74 per cent of unburnt carbon, while with mechanical stoking it is 2·0 per cent under good conditions, and is often 5·0 per cent.

(3) *Flexibility in fuel burnt.*—Pulverized fuel is more flexible in this respect than mechanical stoking and gives less drop in efficiency as the coal varies.

(4) *Combined working with liquid and gaseous fuels.*—Pulverized fuel will work with liquid and gaseous fuels in a manner not possible with mechanical stoking.

(5) *Overload and flexibility in steam output.*—Pulverized fuel is much more flexible in this respect, will get up steam much quicker and will take a heavier overload.

(6) *Stand-by and banking losses.*—These are almost entirely eliminated with pulverized coal, and, in the case of a plant with fairly long periods of comparatively limited steam demand this corresponds to 2–5 per cent saving in the coal bill.

(7) *Ease of scientific control.*—Pulverized fuel lends itself to the latest methods of scientific control from a distant switchboard, in a manner almost impossible with mechanical stoking.

(8) *Labour costs.*—The labour costs with pulverized coal are approximately 20 per cent less than with mechanical stoking, but much depends on individual conditions.

(9) *Auxiliary power consumption.*—The total power consumption in the preparation of the fuel is about 19½ kW per ton, or 1 per cent of the steam production, whilst the very best stoker practice is also about 1 per cent of the steam production; but average figures are 2–3 per cent.

(10) *Maintenance costs.*—It is difficult to obtain these figures for mechanical stoking and, in a lesser degree, for pulverized fuel also. Generally, however, pulverized fuel is superior, and the pulverizing plant itself costs less than 1¼d. per ton, whilst the wear and tear on the brickwork is less than in the case of mechanical stoking.

(11) *Danger of explosions and fires.*—This danger is now much reduced because of simple vertical driers and modern design of burners, but it is still greater than in the case of mechanical stoking.

(12) *Ash troubles.*—With the most modern plant about 17½ per cent of the very fine ash is discharged from the chimney top, and this is stated to give no trouble, although opinions differ. Slagging has been eliminated, whilst mechanical stoking has to contend with the conveying of ash and clinker.

(13) *Capital costs.*—It is difficult to give general figures, but the situation seems to be that for smaller plants mechanical stoking is cheaper, that there is little difference for medium-sized plants over 10 000 kW, whilst for very large plants pulverized coal is cheaper.

It is, therefore, not altogether an easy problem to decide whether for a new plant pulverized fuel should be used in preference to mechanical stoking, and especially for replacing existing mechanical stokers. The efficiency is by no means the only factor, as shown in the paper, and in comparing the two systems of firing we have particularly to take into account the flexibility of steam output, the quality of the fuel, the convenience for individual conditions, and the running costs. Further, the correct design of details, for example the exact position of the firebrick walls, is very important, even when all the modern ideas described are embodied.

Although the principle of pulverization is applicable to a very wide range of fuels, with practically no difference in efficiency, it is interesting to note that the ideal coal for pulverizing has 30–40 per cent volatile matter, low sulphur content, and less than 10 per cent of ash, and has also a high melting point, i.e. it is a highly volatile fuel with low non-fusible ash content. As the volatile content is reduced, the coal is relatively somewhat less easy to ignite and the effect on the brickwork is more severe. There is, however, no real difficulty except in the case of anthracite with less than 5 per cent of volatile matter, and it is claimed that this can be burned if the grinding is finer than usual, the combustion chamber being reduced in volume so as to get the maximum help from the incandescent brickwork. In addition, high ash content generally increases the cost of pulverizing and preparation per unit of steam output, and factors of this description show how complicated is the comparison. It is a significant fact, however, that pulverized fuel has developed to such a remarkable extent in so short a time, although one has to remember the enormous amount of preliminary work that has been necessary to perfect the details that have finally resulted in the present success. It is stated that one company has spent over £300 000 during the past seven years in this field, which again illustrates the great experience American engineers have had with pulverized fuel and the uselessness of experimenting afresh in British power stations with the fundamental principles of this method.

Another significant fact is that many of the newest, most up-to-date and largest power stations in America have adopted pulverized fuel. Thus the Ford Company spent two years in a most exhaustive investigation of the performance of almost every type of mechanical stoker as compared with pulverized fuel, and for their conditions chose the latter. The engineers responsible for the Cahokia station at St. Louis also went to extreme lengths in a similar investigation, and decided on pulverizing for the inferior Illinois coal, and the Detroit Edison Co., well known to be one of the most efficient in the world in the field of power, are only going to adopt pulverized coal after a similar lengthy consideration. Finally we have the facts that the Lakeside station, after three years' experience, is doubling its plant, like the Ford Company; that the Union d'Électricité, after sending their engineers to America, are installing pulverized fuel at Vitry after equipping the largest station in Europe (Gennevilliers) with mechanical stoking; and that such stations as Cleveland and Colfax are now adopting the same principle, although the latter is one of the most efficient stoker plants in the world.

These facts require serious consideration, although it must be remembered that many of the largest American stations, such as Hell Gate, Calumet, Connors Creek, Hudson Avenue and Crawford Avenue, have not adopted pulverized fuel, whilst a limited number of stations are said to be obtaining, as regards the net yearly performance, results nearly equal to those where pulverized fuel is used, and the decision to adopt or reject pulverized fuel has in a number of cases been a very close one.

Pulverized-fuel firing has, however, another very important aspect which is certainly not yet realized. The power stations of Great Britain are burning raw coal to the extent of something like 7 million tons per annum, and are consuming in the process about 21 million gallons of motor spirit, 3½ million barrels of oil (of which at least 50 per cent is Diesel oil), and 63 000 tons of sulphate of ammonia, which latter ought to be employed as artificial manure. These figures

represent the valuable products that could be obtained by the low-temperature carbonization of the coal, a process which the author believes we shall be compelled to adopt in the future so as to eliminate black smoke and render ourselves independent of the world for motor spirit, oil, and fixed nitrogen. The residual low-temperature fuel, with, say, 3–12 per cent volatile matter (the figure depending on the process used) would then be available for steam generation, and is decidedly more efficient than coal, as it burns smokelessly with a high emission of radiant heat.

Pulverized-fuel firing is of the greatest importance because it lends itself particularly well to the burning of this low-temperature fuel, and would enable us to use economically a number of low-temperature processes in which the maximum oil yield is obtained, but where the residual fuel is already semi-pulverized and not suitable for household purposes without briquetting.

It is significant that the Ford Company are now actively investigating the Caracristi and Piron low-temperature process, which consists in carbonizing roughly-pulverized coal on a travelling iron-plate conveyer swimming on a huge bath of molten lead at 1200° F. The object is to recover the valuable low-temperature products, particularly motor fuel, in which of course the Ford Company are particularly interested, and then to burn the residual low-temperature fuel, containing 10–12 per cent of volatile matter in the pulverized condition, under the boilers at River Rouge now using pulverized raw coal.

Finally, also, the principle of pulverized fuel is being actively investigated for the burning of lignites and Esthonian shales; for the carbonization of coal, in which the process is almost instantaneous, even for low-temperature methods; for the total gasification of coal in conjunction with steam (producer gas); and in the manufacture of briquettes without the use of pitch or other binder.

Discussion before The Institution, 13 December, 1923.

Sir James Kemnal: The firm with which I am associated has followed the development of this method of firing with great attention, and, while the use of pulverized coal fills a want in many cases, we do not recognize it as of universal advantage or capable of being used in every instance, as the author appears to think is the case. The Lopulco system, in the main, differs only from other systems of conglomerating various mechanical appliances in that it embodies the water screen, which is, from the boiler constructor's point of view, a somewhat crude arrangement. I do not know from practice what advantage the water screen possesses. We are told that it prevents the ash from forming the glass-like substance which was common when pulverized coal was first used; but, using the unit system, we have found that if we make the furnace 20 to 30 ft. high the ashes are quite innocuous and can readily be removed, so that it does not seem to be an advantage confined entirely to the Lopulco system. The fact that the nature of the ash varies with the nature of the coal is not mentioned. American coals, as a rule, are much more friable than any coals with which we have to deal in Europe, and that has been shown by the fact that whereas in England we cannot use a mechanical stoker more than about 9 ft. wide, in America mechanical stokers to a width of 24 ft. are used. The idea of pulverized fuel is based upon an imitation of the advantages obtained from burning liquid fuel, and the theoretical amount of air required can be ascertained very closely. The disadvantage of pulverized fuel lies, however, in the amount of apparatus required. The author contends that a greater variety of fuel can be utilized than is the case with mechanical stokers. That is not my experience. The quality of fuel that can be utilized in the powdered form is much more limited than in the case of mechanical firing. In fact, it has been found that there is practically no kind of fuel that cannot be burnt in the latest design of Babcock and Wilcox stoker. In Russia both peat and Russian anthracite have been burnt on it, and in England we burnt any small coal, even coal and coke dust. The author makes a great point of the higher efficiency obtained, but a central-station engineer does not care very much whether he is getting 80 per cent efficiency or 85 per cent, so long as his total costs per unit generated are less. The cost of the installation, of which no mention is made in the paper, is a very vital matter. I take it that the cost is very high, probably five or six times as much as that of mechanical stokers of the best kind. I agree with the author that the cast-iron economizer has been an excellent servant, but the pressures that are common nowadays render it less suitable. Although the author may not be aware of it, there are too many cases of cast-iron economizers being replaced by steel economizers for his assertion to be taken as representing altogether the facts of the present day. With regard to the increase in boiler capacity achieved by the use of pulverized fuel, I can affirm that there are many instances in which the same results are obtained with mechanical firing. The amount of evaporation per unit of heating surface is not necessarily a criterion. A heating surface can be so worked as to evaporate 24 lb. per sq. ft. We have done it experimentally, and no doubt it can be done for a peak load, but that is not the point that the designer or engineer of a central station has to consider. On page 386 the author says: "In very few power stations—at any rate in Great Britain—is there any real idea of the efficiency of the steam generation from week to week." The statistics published by the Electricity Commissioners show, however, quite a different result and make it clear that, so far as the generation of electricity is concerned, accurate records are kept which will act as a valuable guide. In addition, of course, there are a great many private installations in which the cost of power is carefully established. The author states also that British power station practice is far behind that in America, but this is by no means my experience. Pulverized fuel is no doubt very good, but it is not everybody's good luck to make it successful, nor everybody's business to use it.

Mr. G. W. Partridge: Pulverized fuel has certainly come to stay. At the same time, when the author refers to the high efficiencies he gets, I do not think that he has taken into consideration all the improvements now being made in the present mechanical stokers. I agree with Sir James Kemnal that one of the chief concerns of the power station engineer is not so much the efficiency of his boiler house as the final and total cost of evaporation, which should include cost of labour, repairs and maintenance, and interest on capital. With regard to the capital cost, the author simply states in the summary of the paper that capital costs were difficult to obtain. It would be instructive to learn what these costs are in the case of pulverized-fuel installations compared with the present mechanical-stoker plant. I am not altogether certain that a comparison between the American tests and those made in this country is very convincing. The fuel used in America is not by any means similar to that at the disposal of the average power station engineer in this country. I notice that the average calorific value of the American coal mentioned in the tests was over 12 000 B.Th.U.'s. The engineers in the London area have hundreds of different classes of fuel at their disposal of various calorific values, etc., and at various prices. It is of great importance to have a stoker that will burn at a reasonable efficiency any class of fuel without any preparation such as drying and grinding beforehand, and I can quite conceive a power station burning a low-class fuel at a moderate efficiency with a lower cost of evaporation than that of a station as described by the author with the high efficiency which he claims, but with a very much higher initial capital cost. Some years ago we were thinking of installing a powdered-fuel plant in London, but every engineer whom we consulted told us that one of the main disadvantages was that dust was ejected from the stack. The author, however, says that the ash thrown out is not seen again. The particular power station of which he speaks is situated at the side of a lake, so the ash probably falls into the lake when the wind is in the prevailing direction. The London area is a very different proposition, particularly when one has to consider the stringent rules and regulations of the County Council and district surveyors. At the same time I think that there is a great deal to be said for the use of powdered fuel in the future, more particularly as regards Kent coal, which is mined only a short distance from London and has a high volatile and calorific value.

Mr. B. Pochobradsky: Boiler-firing is a difficult subject, and in endeavouring to compare systems we must examine very carefully the results already obtained. The paper compares the pulverized-fuel firing at the Lakeside power station with the mechanical stoker at Dalmarnock station. It is stated that the boiler efficiency over an extended period at Lakeside is 85 to 86 per cent and at Dalmarnock 76 to 77 per cent, and it is claimed that this difference in the efficiencies is due to the methods of firing. This claim appears to be erroneous, as can be seen from the figures in the paper. Let us compare the test taken on the 21st March, 1923, at Dalmarnock (Table 6) with Lakeside test No. 3 (Table 8). These two tests show practically the same CO_2 content and therefore one difficulty of comparison is removed. That is my reason for choosing these two tests. It should be noted that the coal used for the Dalmarnock test contained 14·8 per cent of moisture as against 3·59 per cent at Lakeside. The difference in moisture has nothing to do with the system of firing, but incidentally it influences the boiler efficiency. The loss in efficiency due to moisture at Dalmarnock is 1·5 per cent and at Lakeside 0·4 per cent. Had the same coal been used at Dalmarnock as at Lakeside, the boiler efficiency at the former station would have been 1·1 per cent higher, solely on account of the smaller moisture content. A further and more important factor is the temperature of the flue gases at the economizer outlet. At Dalmarnock this is 414° F. as against 205° F. at Lakeside. I propose again to use the author's figures to translate these temperature figures into efficiency figures. Table 7 contains under No. 3 the same test as Table 8. In Table 7 we find that the efficiency of the boiler with superheater is 82·5 per cent, which corresponds to a flue-gas temperature of 482° F. (leaving boiler), and the efficiency of the boiler, superheater and economizer is 87 per cent, which corresponds to a flue-gas temperature leaving the economizer of 205° F. In other words, to a difference in flue-gas temperature of 277 degrees F. corresponds a difference of 4·5 per cent in efficiency. Applying that to the two tests we are comparing, we find that the difference in leaving temperature between Dalmarnock and Lakeside is 210 degrees F., which means a difference in efficiency of about 3·4 per cent. Taking the steam duties of the two tests into account, we find that the Lakeside boiler has 66 per cent larger heat-transmitting surface in the boiler and 29 per cent larger heat-transmitting surface in the economizer for each pound of steam generated. It is beyond doubt that this enormous difference in the heat-transmitting surfaces of the two boilers is the principal cause of the leaving temperature at Lakeside being so much lower (naturally the boiler cost is increased) than at Dalmarnock, and, what amounts to the same, the principal cause of the efficiency of the boiler at Lakeside being higher. It is obvious that the extraction of heat from the flue gases, particularly near the exit, has nothing to do with the system of firing, and therefore the increase in efficiency experienced at Lakeside cannot be credited to the central pulverizing plant. The efficiency at Lakeside in the test under discussion was found to be 87 per cent and at Dalmarnock 83·56 per cent. If we correct the Dalmarnock test so as to bring it to the same basis of moisture in coal and the same ratio of heat-transmitting surfaces (or what amounts really to the same thing, the same leaving temperature, both of which factors are independent of the system of firing), we find the efficiency at Dalmarnock to be $83 \cdot 56 + 1 \cdot 1 + 3 \cdot 4 = 88 \cdot 06$ per cent, as compared with the Lakeside efficiency of 87 per cent. It is these two efficiency figures which are directly comparable if we desire to compare the performance of mechanical-stoker firing and pulverized-fuel firing, as we have eliminated factors which have nothing to do with the system of firing itself. These figures are test figures. We should consider as being more important, not the

test performance but a performance over an extended period. The boiler efficiency at Lakeside over an extended period is stated to be 85 to 86 per cent (or an average of 85·5 per cent with 60 per cent load factor) and 76 to 78 per cent (or an average of 77 per cent at Dalmarnock with 34 per cent load factor), or, on the author's assumption, 78 per cent if Dalmarnock had the same load factor (60 per cent) as obtained at Lakeside. These Dalmarnock figures for an extended period, compared with the test figure of 83·56 per cent (with the actual heat-transmitting surfaces and coal used at Dalmarnock and uncorrected), show that the boiler efficiency at Dalmarnock for an extended period is 5·56 per cent lower than the efficiency obtained on test. It is obvious that had the same wetness of coal and same ratio of heat-transmitting surfaces been available at Dalmarnock as at Lakeside, this loss of 5·56 per cent would still have taken place, as compared with 1 per cent at Lakeside. The difference, viz. 4·56 per cent, is due to firing systems, and it is here that pulverized fuel has a decided advantage. Having found that the test efficiency, reduced to the same coal moisture and leaving temperature as obtain at Lakeside, is 88·06 per cent at Dalmarnock and 87 per cent at Lakeside, we come to the conclusion that for identical boilers, but with mechanical stokers as installed and operated at Dalmarnock on the one hand and pulverized-fuel firing as at Lakeside on the other hand, the efficiencies over an extended period are: With mechanical stokers $88 \cdot 06 - 5 \cdot 56 = 82 \cdot 5$ per cent, and with pulverized-fuel firing 85·5 per cent. These figures, however, do not give us the final comparison. It is not merely a question of heat efficiency that determines the respective advantages or disadvantages, but the final criterion is the overall economy. It is necessary to take into account the consumption of auxiliary power, labour, first cost of plant and buildings, maintenance and repairs. It is highly probable that the first cost of plant and buildings for the central pulverizing plant at Lakeside is substantially higher than that of mechanical stokers at Dalmarnock, but as no figures are given in the paper I do not feel justified in making a comparison. I shall also disregard the cost of maintenance and repairs for the same reason, and compare only the auxiliary power and wages. In Table 12 the power required in the pulverizing building at Lakeside is given as 1·78 per cent of the total power generated, and the electrical energy required for boiler-house auxiliaries is given as 0·34 per cent (this latter figure obviously not including feed pumps and fans, which are steam-driven). It includes the power necessary in connection with pulverized-fuel firing and probably for handling ash. The total of this auxiliary power represents 2·12 per cent. The corresponding power at Dalmarnock is that required for the mechanical stoker which, according to Table 6, is 25 kWh for 28·7 tons of coal, or 0·88 kWh per ton of coal. This means, assuming with the author that 19½ kWh is equivalent to 1 per cent of the total steam production or of total power production, less than 0·05 per cent of total steam or total power production. To this figure we ought to add a fraction of 1 per cent on account of ash-handling, which seems to have been included in the figures for Lakeside. We will assume, in the absence of correct comparable figures in the paper, that to the figure of 2·12 per cent as the consumption of auxiliary power at Lakeside, corresponds 0·25 per cent of power consumption at Dalmarnock. Further, from the paper it appears that the wages, by using a central pulverizing plant, are increased by about 5d. per ton of coal, which means, assuming coal at 20s. per ton, 2·08 per cent of the total steam or power production. The coal-handling in both stations, assuming equivalent circumstances, will show no appreciable difference, as in one case the coal has to be transported to the pulverizing station and in the other case to the boiler house. The boiler-house wages appear in both cases to be very similar, so that the overall economic efficiency, considering the difference in auxiliary power and wages, becomes for the mechanical-stoker plant $82 \cdot 5 - 0 \cdot 25 = 82 \cdot 25$ per cent, and for the central pulverizing plant $85 \cdot 5 - 2 \cdot 12 - 2 \cdot 08 = 81 \cdot 3$ per cent. The author mentions that certain improvements are obtainable with the central pulverizing plant, which, if they are realized, would make the overall economic efficiency equal to that obtainable with the mechanical stoker, disregarding the higher cost of plant and buildings at Lakeside. These figures indicate no superiority of the central pulverized-fuel plant over the mechanical stoker. The author's claim that it is very much better and that the difference in boiler efficiency indicates the degree of that superiority, is a fallacy. I agree that pulverized fuel is better as regards flexibility and that it reduces the stand-by and banking losses, but when we compare systems of firing and means used to effect such firing, we must strive to eliminate from our comparison factors which have nothing to do with the firing. On the other hand, we must include all factors which have any influence on the overall economy or on the total cost of the generated power. The main reason for the central pulverizing plant at Lakeside showing no advantage over the mechanical stoker at Dalmarnock is in the large amount of auxiliary power and in the excessive wages. Had the paper given also the first cost, I believe that the central pulverizing plant would have been shown at a disadvantage. In comparing the systems of firing, and particularly in speaking about pulverized fuel, we must remember that there are two systems of pulverized-fuel firing, the central pulverizing plant and the unit system. The unit system will, on an average plant, show a first cost about equal to that of mechanical stokers and naturally substantially smaller than that of central pulverizing plant. On large plants the unit system will be cheaper than the mechanical stoker and cheaper also than central pulverizing plant. The power consumption on the unit system will be lower than for the central pulverizing plant, viz. about 25 kWh per ton of coal, including pulverizing and delivery of coal and all air required for combustion into the furnace. This represents about 1·3 per cent of steam generated, as compared with 2·12 per cent required for the central pulverizing plant. The wages in the case of the unit pulverizing system will be substantially equal to those necessary in the case of

the mechanical stoker, so that the unit system is likely to prove superior to the central pulverizing plant and the mechanical stoker by about 3 per cent in the overall economy. To illustrate the difference in cost of pulverizing plants, I would take the figure given in the paper, viz. £11 562, as the cost of pulverizing plant to deal with 50 tons a day. A unit pulverizer for the same duty would cost about £800. The efficiency of firing, whether unit pulverizer or central pulverizing plant is used, will be exactly the same, as the performance of a unit pulverizer is in every respect equal to that of a central pulverizing plant. While even the unit pulverizer will not in every instance be found superior to the mechanical stoker in overall economy, undoubtedly it will prove to be so in a great many cases. One special case requires prompt attention, and that is the utilization of waste coal which can be burned very efficiently in pulverized form. Here the unit pulverizer will render particularly valuable service. It goes without saying that if the so-called waste coal is utilized its price will rise. On the other hand, the production of coal generally will be cheapened because the collieries will have in the waste coal a new source of revenue. In the end the average price of coal will undoubtedly be reduced, and thus the pulverizer will contribute towards the cheapening of power production generally.

Mr. D. Wilson: The statistics given in connection with pulverized fuel are very clearly set out, but I feel that it is a pity that the author has rather obscured the issue by admitting irrelevant matter. He states that he has carried out 400 boiler tests, but those of us who have studied these tests will ask what possible bearing they can have on the issue raised. The results of these tests, if accepted, only go to prove that the operations were poor, and not necessarily that the design was bad. There is an underlying suggestion in the paper that we are lagging far behind America in this question of powdered fuel. The American lead is the Milwaukee lead, and, considering the size of the two countries, the rest of America seems more slow than England to follow this lead. We are told that up to the middle of 1923 only 9 Lopulco systems were installed, but it would have been instructive if the author had extended his inquiries and given some comparative figures. He would then have found that the total heating surface of stoker-fired boilers would have greatly exceeded his figures for powdered coal. What is his case? Briefly, it is that at Lakeside the average day-to-day efficiency is 85 per cent, and that the comparable figure for stoker firing is 81·5 per cent. The author is well aware that a difference in degree of supervision in a power station may mean a great difference in the percentage of efficiency. In fact, he himself confirms this when he says that the attention at Lakeside is far above the ordinary. He goes on to say that with extremely good attention pulverized fuel would probably give 82·5 per cent efficiency, whereas the mechanical-stoker plant figure would be 75 per cent. This latter figure must, I think, be a misprint. I can give the author instances of day-to-day efficiencies of 80 per cent with the mechanical stoker, and this on an ordinary plant, and not a modern one at that. The author admits that there has been a great advance in mechanical-stoker firing during the past few years, and I believe it is admitted in America that on test there is not much advantage, if any, in powdered-fuel firing. Thus we come to the last claim made for powdered fuel, namely, flexibility. Here, however, I am not so sure that station engineers would be in agreement. Modern stokers will give a high degree of flexibility. The Birmingham Corporation alone burn about 1 000 tons of coal per day, using coal of about 8 000 to 9 000 B.Th.U.'s, and obtain full load with this fuel. On the same plant they can obtain full overload duty when burning coke fuel with only 5 per cent volatile. We have yet to learn that powdered fuel will cover such a range as this. The author refers to Milwaukee fuel, giving a figure of 11 500 to 12 000 B.Th.U.'s as a low-grade fuel, but it would not be called low-grade in this country. A figure of 9 000 or even 7 000 B.Th.U.'s would come within that description, and we burn such coal on stokers. The author's figures, therefore, are unlikely to be accepted as representing boiler practice in this country. The author states that the efficiency with pulverized fuel is 85 or 86 per cent, but the Lopulco guarantee is confined to 84 per cent on test. If they are so certain that they can obtain 85 per cent day-to-day efficiency, why do they not guarantee something higher for test efficiency? A guarantee given in this country under penalty for the test efficiency of a stoker plant is 86 per cent. I think that the author's quotation with regard to carbon ash is inaccurate and liable to mislead. In a well-operated station the carbon in ash does not exceed 10 per cent, which, in the case of such coal as is used in America, would mean a loss of under 1 per cent, and indeed there should be no difficulty in keeping the loss down to 0·5 per cent. I agree that powdered-fuel firing must receive very serious consideration, but there are many doubtful factors to be eliminated before the suggestions made in the paper can be accepted. We know that Americans are much more ready to accept a new invention than we are in this country, but British station engineers are as capable of progressive endeavour as are Americans.

Dr. R. Lessing: I should like, as a chemist, to address myself to one particular point, namely, the question of the amount of ash in coal. It seems to me that this factor is very important in considering this problem. The disposal of ash from pulverized-fuel plants is a very serious problem. Even if only 12 per cent of the ash escaped through the chimney, it would mean that our vanishing smoke-problem was being replaced by a dust problem. I feel that the question of ash in coal—that is to say, the inorganic constituents of coal which we find in combustion in the form of ash—has not received the amount of attention from power engineers that it deserves. From the work which I and others have been doing during the past six years, we know to-day that in average coal about 60 to 70 per cent of the fuel contains not more than 1½ to 2 per cent of ash. The remainder of the coal would be rather higher in ash content, i.e. from 6 to 7 per cent. All the ash received in excess of these figures does not belong truly to the coal at all. It is extraneous ash which could easily

be eliminated from the coal at the colliery. In this country we are carrying from 25 million to 40 million tons of ash an average distance of 50 miles, and this engages 10 per cent of our entire mineral traffic. If only a portion of this ash were eliminated, either at the colliery or at some subsequent stage, an enormous saving would be effected which would allow us to pay more for the refined coal without adding to the ultimate cost. I should like to refer in particular to the difficulty of grinding the mineral portion of the coal. I have figures which show that a clean coal would give in the grinders a considerably higher "through-put" than would dirty coal at the corresponding rate. A further advantage would be that the erosion of the burners and also of the firebrick walls of the combustion chamber would be stopped or reduced. From all these points of view I think that it is one of the essentials for a successful solution of the powdered-fuel problem that ash should be eliminated. It is, I feel, rather futile for those who wish to promote the introduction of powdered-fuel installations to endeavour to persuade engineers that they can burn coals with a high percentage of ash. They are doing themselves a great injustice. It would be more advantageous to insist on a high grade of fuel being supplied to them. I believe that if such a reduction in ash could be effected the pulverized fuel would be on a par, or nearly so, with liquid-fuel firing and even with gas firing, and no doubt very great advantages would be realized.

Mr. F. F. Evans: I know from experience that there are very grave disadvantages in dealing with the large number of coals of varying qualities which are continually met with even in any one station. I know also that, even with the most highly organized system and the best type of mechanical stoker, where 19 or 20 classes of coal have to be dealt with it is extremely difficult to obtain highly efficient results. The reason is, to some extent, the want of training of the operators. What has not as yet been mentioned in the discussion is the reason why pulverized fuel is bound, sooner or later, in this country to come to the front as a means of solving a great many important problems. Turbines having capacities anywhere between 15 000 and 25 000 kW are now being made and operated. Taking an ordinary station such as Glasgow, this means that five 60 000-lb. boilers are required, with a sixth possibly as a stand-by. If one lays out a station of, say, 75 000 kW, or even 40 000 kW, it is obvious that the housing of these boilers, together with all their accessories, must involve a considerable capital cost. If, on the other hand, large boilers are installed, it is found at once that the difficulties in connection with mechanical stoking are very great. At Manchester, boilers evaporating from 115 000 to 130 000 lb. of water are at present installed. In connection with each of these boilers there are four mechanical stokers. If the necessity for larger boilers arises, as I foresee it will do in time, about eight large mechanical stokers will have to be installed for each boiler. In other words, the possibilities of a breakdown will be increased eight times. On the other hand, if powdered fuel is used, a system will be obtained by which, even in the event of one of the burners going out of action, the load on the boiler can at once be taken up without the slightest difficulty. It is not likely that the whole of the burners will fail simultaneously. The case for the large boiler will in the future be very definitely established, and from a mechanical-stoker point of view I think that it will provide a very serious problem. At the present time large quantities of grit are being emitted in these mechanically-stoked systems. It is true that the emission of waste matter from a powdered-fuel installation may be greater or less than that in the case of mechanically-stoked systems, but it is not grit; it is a fine flocculent dust. The Medical Officer of Health in Milwaukee has his offices immediately opposite the Lakeside plant, and in the course of four or five years' observation has never had to complain in any way of the emission of either grit or smoke. It will be said at once that the ash must settle somewhere. No doubt it does, but it settles in such a form that it is not objectionable, and its own light flocculent nature and the varied conditions of the wind cause it to be distributed over long distances. I should like to say, with regard to some remarks made earlier in the discussion, that my company are at present manufacturing mechanical stokers 16 ft. in width, and we see no reason why that size should not be increased. No mention has been made of the fact that in a great many stokers the question of riddlings is a very serious matter. My company have been considering the installation of an ash-conveying plant at a London station, and we found that we should have to install in addition a separate system for conveying the riddlings which, we were informed, would amount to 20 per cent of the total amount of coal used in the stoker. This difficulty does not arise in the case of powdered fuel, and the added expense of a separate conveying system for the riddlings is unnecessary.

Mr. W. M. Mordey: In the early part of the paper the author refers to the work of Thomas Russell Crampton. It is very interesting to know that the distinguished engineer who perhaps did more than anybody else in an early stage to recognize the possibilities of powdered fuel, who actually went so far as to put it into practice and conceived many of the important elements necessary to success in practical work, was a member of the Council of this Institution. Although primarily a railway engineer, he was one of the leaders in submarine telegraphs. When the first cable to France failed he designed a new and successful cable and raised the money for it. When he died in 1888, Edward Graves, then our President, described him as the author of the type of submarine cable that had come into use throughout the world.* That was a great achievement. As one of the few here who remember him, it is perhaps fitting that I should remind members of the debt that electrical engineers owe to his memory.

Mr. J. S. Atkinson: It is a matter of regret that the author should have disposed of unit pulverizers in such a few words. I think that as British engineers we are more interested in the European than in the American standpoint, and the unit system has made far greater progress on this side of the Atlantic than has the central system. The author may be surprised to learn that there are over 400 turbo-pulverizers installed and working

* See *Journal I.E.E.*, 1888, vol. 17, p. 421.

in this country and upon the Continent. In addition, there are a number of other types of unit pulverizers now on the market which are giving good results in practice. After Bettington's activities in this country I think that the firm with which I am associated was the first to take up powdered fuel seriously. In the early part of 1918 I paid an extended visit to America to examine the various systems used there, and I came to the conclusion that the central system was better than the unit system. For two years we concentrated on the central system and lost much money and time. We then turned our attention to the unit system and, although we had to face many problems and made many mistakes, I think that we can now say that we have been able to produce a really satisfactory and practical machine. The statement has been made that by reason of the fact that there are no magnetic separators fitted to unit machines, there is a danger of the machine breaking down. Our experience shows, however, that magnetic separators are quite unnecessary; it must be obvious that if an electric separator were a necessary item it could easily be added. The author lays emphasis on the necessity for getting the proper mixture of coal and air; with this I quite agree, but he also makes statements which would imply that it is not possible to get this mixture with the unit system. Practical results have proved that this is not the case. We have had a large number of boiler tests made, many of which show a total efficiency of 85 per cent and higher. The analysis of the waste gases shows that the fuel is burned with not more than 20 per cent excess air, and the unburnt carbon in the ash is well under 1 per cent. I do not think that anyone can expect to get much better results than these. We have never claimed that we can get much higher efficiences with powdered-coal firing under test than can be obtained with good practice in mechanical stokers, but we do claim that we can maintain higher efficiencies under everyday working conditions, and use cheaper grades of fuel than can be efficiently burned with mechanical stokers. It is rather difficult to reconcile the author's present attitude with regard to the unit system with his attitude as expressed in an article which he wrote in the *Iron and Coal Trades' Review* of February 1922.

Mr. P. M. Baker (*communicated*): The author has brought up the subject of boiler-house efficiency, with its corollary of boiler testing, in a new form. Its importance will be obvious to anyone who has read the Electricity Commissioners' annual returns, in which some of the figures are astounding. My first impression was that the author would have done better to have taken the broad view and dealt with all types of pulverized-fuel plant, but further reading convinced me that the course which he adopted, viz. to deal with a particular system and one or two examples thereof, makes a stronger case for pulverized fuel than would otherwise have been possible. The treatment of this particular case is very comprehensive, and the amazingly good results shown in the test tables can only be answered by corresponding figures for mechanical stokers. Unfortunately it is only very large installations that can yield results comparable with those given in the paper, so that very few engineers are in a position to put up a case for the mechanical stoker. I desire strongly to support the author's opinion in regard to boiler tests. An acceptance test should be run under the conditions specified in the contract; the plant should be in the best condition possible, and the test figure should be an optimum. This is not sufficient, however; tests and records should be practically continuous. If we except some of the good and new stations it seems fair to state that the boiler house is still the neglected end of the generating station, and that the instruments installed in it are often covered with dust and cobwebs between tests, which take place at infrequent intervals, when a little careful organization and systematic work would enable a fairly continuous record of the behaviour of the steam-generating plant to be kept, however large or small it might be. The idea that there is no need for the central station engineer to be very strongly interested in the thermal efficiency of his boiler plant may perhaps be responsible for the small attention it receives in some stations, but it cannot be too strongly impressed on all fuel users, of whom the central station engineer is one of the largest, that it is of the utmost national importance that every possible heat unit should be utilized, although it is, of course, realized that a system of stoking which would enable the low-grade fuel hitherto regarded as waste and unusable to be burnt, would justify some loss of thermal efficiency. The author claims that such fuel can be burnt efficiently in a pulverized form. The reply of the users of mechanical stokers as to what their plant can accomplish, particularly in districts in which cheap, low-grade slack is abundant, would go far towards deciding whether we ought to adopt pulverized-fuel firing in this country, for the available coal is likely to deteriorate as time goes on and labour difficulties increase. My own experience, with a very small plant, of dirty and low-grade Indian coal burnt on a chain-grate stoker was not very encouraging. Possibly some station, such as Birmingham (Nechells), would afford very instructive figures, as I understand that much good work is being done there with low-grade slack. The vexed question of the standardization of boiler tests and the Institution of Civil Engineers' Code is again raised in the paper, and in that connection I submit that our Institution is probably much more truly representative of those coal users most concerned with the economical consumption of coal in large quantities than any other, and that we ought to take energetic measures, either in conjunction with the Institution of Civil Engineers or independently, to lay down a satisfactory standard scheme for (*a*) acceptance, and (*b*) running tests, in order to enable fair comparisons to be made.

Mr. J. R. Blaikie (*communicated*): It is interesting to note that the author thoroughly approves of the methods of testing, etc., at the Dalmarnock station, and also that in his opinion the results might be improved by larger combustion chambers and stokers of the "compartmenting" type, and that air-heating alone might raise the efficiency to 80 per cent with a 60 per cent load factor. On the question of combustion chambers the author says on page 400: "One of the chief causes of inefficiency of the mechanically-fired boiler plants in Great Britain is that the tubes of the

boiler are far too near the furnace, so that the flames touch the boiler long before combustion is completed, and the reactions are at once damped down with the escape of unburnt fuel." On page 402 the author quotes from his own personal experience of 400 tests, mostly on boilers of the Lancashire type, individual figures varying from 32½ to 82½ per cent. Is it correct to say that efficiencies of 82½ per cent can be obtained from a Lancashire boiler plant when the furnace is within a few inches of the boiler surface, and, if so, what is the explanation? An interesting point about Dalmarnock is the use of two kinds of mechanical stokers. I should like to know whether one type is intended for a particular class of fuel and the other for another; whether they are in competition on similar fuel; whether it is a case of balancing higher efficiency against extra capital cost; or whether it was simply the result of the lowest tender. The "compartmented" type of stoker, with a positive means of controlling air pressure in different sections to cope with the varying resistance of the fuel bed as combustion progresses, should certainly make an appeal in well-organized boiler houses. Probably the reason that this type is not more extensively used is its high capital cost. Now that this type can be obtained at rates no higher than those in the case of an ordinary chain grate, considerable improvements may be expected in mechanical stoking. I should be glad if the author would give a few test figures of this type to set against the individual boiler tests with pulverized fuel on No. 8 boiler at Lakeside. The author has chosen Dalmarnock as being representative of mechanical stoking chiefly on account of the overall size, which compares with that of Lakeside, but I suggest that the choice might have been better justified for the reasons that the testing department is so highly organized, and that the willingness of this undertaking to supply and make public its records is on a scale which compares with the large-mindedness of American organizations in this respect. The paper is mainly concerned with the thermal efficiency of steam generation. It is true that laudable efforts have been made to obtain the capital costs of pulverized-fuel plants, but the corresponding capital outlay on large-scale mechanical-stoker plant is lacking. On page 416 a comparison of operating costs is submitted in a highly complex form. We are given the net cost, expressed in dollars, per 1 000 lb. of steam at unknown pressure and superheat, to compare with American stoker plant also at unknown pressure and superheat, price per ton, etc., expressed in dollars per ton (American) of fuel. The Dalmarnock figures are expressed in pence per kWh delivered, and the item "Shift Wages and Salaries" seems to cover both engine room and boiler house. Can the author arrive at the cost of, say, 100 000 B.Th.U.'s above the temperature of the raw materials delivered from the boiler house in pence or dollars from this data, or otherwise demonstrate his conclusion No. 8, viz. "The labour costs with pulverized coal are approximately 20 per cent less than with mechanical stoking, but much depends on individual conditions"? Assuming that the difficulties of obtaining information as to capital costs and operating costs are too great, we fall back on thermal efficiency, strictly confined to boiler-house operation. From this standpoint the choice of Dalmarnock which, according to the author, is open to criticism in the selection of stoker plant, stands in need of justification. There is no need to go beyond the boiler unit in size. In this country we have no boiler to compare in size with American boilers, but there are numerous examples of boilers, similar in size to those at Dalmarnock, which may possibly have attained higher efficiency with mechanical stoking. Turning for a moment to the technical data, it is interesting to note that the range of output of the Lakeside No. 8 boiler, at 88·5 and 85·6 per cent efficiency respectively (see Table 7) is from 4·5 to 8·6 lb. of water per sq. ft. of heating surface. It would have been instructive if the tests had gone further to discover the lowest output at which an efficiency of, say, 85·5 per cent can be obtained. This has an important bearing in the matter of load factor. Can the author show what can be done in this direction by the best and latest forms of mechanical stokers? In Table 8 the loss by radiation is given as about 1½ per cent. For Dalmarnock (Table 6) it is given as 2·5 per cent. With the enormous combustion chamber heated to a temperature verging on destruction, a very considerable loss by radiation is to be expected, and I should like the author to comment on this point. In conclusion, I should like to point out that several important stations in America—such as Colfax, Hell Gate and Connors Creek—have no economizers, which fact brings home very forcibly the policy of true commercial efficiency as against that of sensational thermal efficiency.

Mr. W. F. Carr-Hill (*communicated*): The following remarks summarize some of the leading considerations as to the best system of coal pulverizer to adopt for any given requirement. Pulverized coal as a fuel came into serious use in Great Britain about 23 years ago, from which date its use extended rapidly in Portland cement manufacture. In recent years it has been applied increasingly to steam-raising boilers, metallurgical furnaces, etc. For any pulverized-coal proposition to be successful it is essential that the pulverized coal shall not only be ground to the necessary fineness, but that it shall be uniform in quality as regards the distribution of the ash and dirt content in the coal as fed to the furnace. Only some of the systems in use to-day secure this very necessary condition. At the present time three leading systems for pulverizing coal are employed, as follows: (A) Pulverizers giving a finished product to the necessary fineness in one operation; (B) pulverizers which only rough-grind the coal, and deliver it to auxiliary separating appliances, the fines being separated and the rejects returned to the pulverizer for re-grinding; (C) pulverizers of the beater or swing-hammer type, usually of very high speed, which deliver the finished product direct to the kiln, furnace or boiler combustion-chamber. This type usually has a fan combined with the mill to effect delivery of the ground product to the furnace. The relative popularity, uses and operating costs of these three systems may be summarized as follows:—

(A) *Pulverizers giving finished product at one operation.*—There are several types under this heading.

Most of them have a screen fitted to the mill itself and an internal fan device which ensures—

(*a*) The ground product leaving the mill immediately it is fine enough, and not before.

(*b*) Uniformity in the ground product as regards ash content, resulting in the maximum steadiness of flame from the burner. It has been found in practice that this system shows a great advantage over other pulverizing systems which depend on auxiliary separating devices to obtain the necessary fineness of product. These auxiliary methods most certainly result in "selective separation" and stratification of ash content in the ground product due to difference of specific gravity between the coal and the dirt and ash which it contains. This causes a "squally" flame and irregular temperatures in the combustion chamber, with the attendant additional wear and tear, cost of upkeep and loss of efficiency.

The power required is one of the most important items in assessing the relative costs of operating different pulverizing systems, and it can be taken that with the most economical and best type of screen mills the power used will amount to 13–14 b.h.p. per ton of coal ground to a fineness of about 75 per cent passing a 200-mesh screen. (This is about 12½ per cent less power than that mentioned in the paper.)

(B) *Pulverizers depending on auxiliary separators.*—Though these have been used in many plants abroad they have not been so popular in England as the "finish in one operation" mills described in (A) above, for the reasons of non-uniformity of ground product and "selective separation" above referred to. Moreover, this type is usually more costly in power and maintenance, and thus the cost per ton of coal pulverized is higher. The power consumption of this type usually amounts, with auxiliary separators, to about 20–22 b.h.p. per ton ground to a fineness of about 75 per cent passing a 200-mesh screen.

(C) *Pulverizers of beater type.*—The general experience with these seems to be that as the beaters wear quickly, as often happens, it is difficult to keep up the necessary fineness; in fact the fineness falls off badly (which is fatal to perfect combustion and steady temperatures) and the power consumption increases. In an average state of repair, general experience shows that the power required to keep this type of pulverizer running is 40–50 b.h.p. per ton ground to an average fineness of 70–75 per cent passing a 200-mesh screen, varying between the limits given according to the class of coal used.

It will thus be seen that the "finish in one operation" mill containing its own screen as described in (A) above is the most practical and economical pulverizing system to adopt for any purpose, as it secures (1) greatest economy in power and maintenance costs; and (2) the best fineness and uniformity of quality in the ground product (a point of the highest importance for efficient combustion and consistent and economical results).

Mr. F. Clements (*communicated*): The remarks of previous speakers show clearly the need for the paper in order to bring before those controlling the use of large quantities of fuel the considerable progress which has been made with this latest method of combustion. The author mentions the use by the Ford Company at their new plant at River Rouge, Detroit, of powdered coal in conjunction with blast-furnace gas as a fuel for steam generating. I visited the River Rouge plant in 1920, but the combination was not then, I think, installed. I mention this because the usefulness of such a combination has been apparent to me for some years and I was responsible for putting in the first two units of a new battery of Babcock boilers at the works of the Park Gate Iron and Steel Co., Rotherham, on this system. In my opinion this plant pre-dated the Ford installation, but in any case they are the first boilers in Europe using this method of firing. Whilst the plant is in no wise comparable with the Ford plant in size and pretentiousness, yet the experience gained with it proves very definitely the value of the combination and also provides a good indication of the value of powdered coal when used alone. The boilers have each an evaporative capacity of 30 000 lb. per hour at 160 lb. per sq. in. and are equipped with gas burners of new design. The powdered coal is provided by one unit-type pulverizer on each boiler. Each machine is capable of dealing with 2 300 lb. of coal per hour. The combustion chambers are of large volume, and when blast-furnace gas alone is used the full capacity of the boiler can be attained. In the event of the demand for steam increasing still further, the pulverizers are put into service and the jet of burning coal so directed that it finally intermingles with the gas, with the result that the mass in combustion burns with a luminous flame. Under these circumstances it is quite easy to maintain for long periods an output from the boiler of 50 000 lb. of steam per hour. Again, when the furnace gas fails for any reason the powdered coal is used and the boiler evaporation maintained. Naturally with an entirely novel installation, designed without the guidance of previous experience, there are points which would be rectified in succeeding units, but the result on the whole has been so satisfactory that a further extension of the system is certain. Reverting now to the general question of the use of powdered coal, I spent some time during my last visit to the United States in investigating the subject and saw several installations where it is successfully at work. What I learned there, coupled with the experience gained in the use of pulverized coal at the Park Gate works, points to the fact that there is no question as to the superiority of this type of boiler firing. The ease of control of the flame and the perfect combustion attainable renders it equal to a plant burning oil as fuel, and indeed the whole of the summarized advantages of the method, as given by the author, are fully supported in practice. The chief difficulty is the one which the system referred to by the author is designed to overcome, viz. that due to slagging of the ash. This difficulty is not present with all coals because those which have ash in which lime predominates give little trouble, but the possibility is always acutely present. Any system installed for burning large quantities of powdered coal must be guaranteed to have overcome this trouble satisfactorily.

Mr. J. M. Duncan (*communicated*): (1) The mechanical-stoker equipment at Dalmarnock appears to be of conservative design in the light of current American practice. Stoker-width limitations which the sprung arch entail have been removed by the perfection of the flat suspended arch, and full use has been made of this in the successful operation of stokers 24 ft. wide by 18 ft. long. In the Calumet station of the Commonwealth Edison Co. of Chicago, the operation of this stoker has been so successful that six more have been ordered, three Babcock and Wilcox and three Coxe. The original stoker was installed under a boiler of 15 500 sq. ft. heating surface. The removal from each furnace at Dalmarnock of two division walls, with their attendant losses due to uncontrolled air, clinker formation, etc., which 20 ft. wide stokers would permit, should result in an increased economy and a reduced maintenance cost which would place the stoker in a somewhat more favourable position when compared with pulverized fuel. (2) Some station operation figures at Calumet are as follows: Operating 16 Coxe stokers 10 ft. 8⅝ in. wide by 17 ft. long at 300 to 350 per cent of American boiler rating (120 000 to 160 000 lb. of steam per hour) during the day with a monthly load factor of 28 per cent, the number of B.Th.U.'s per kWh for November 1923 is stated to be the remarkably good figure of 17 800. It would seem reasonable to expect an improvement on this figure when the new stokers 23½ ft. and 24 ft. wide are installed. (3) The banking losses at Dalmarnock are extraordinarily low. The actual charge against stokers for banking, if I correctly interpret the figures given on page 400, amount to less than ½ per cent per hour of full-load consumption, a figure which would not be regarded as out of the way for boiler-radiation losses alone, and would indicate that the loss chargeable to stokers for banking and stand-by is nil in this case. The above considerations would indicate that the author's estimate of 5½ per cent better performance of pulverized fuel over stoker firing in a given modern station might be a little high, and a comparison of maximum guarantees for each type as quoted in the paper would appear to me to justify a somewhat lower figure. But the immense advantage which pulverized fuel has in the burning of low-grade fuels of all varieties cannot be overrated, and I am also of the opinion that for continuous operation the ease of control with pulverized fuel will give average operating results for average boiler plants considerably in excess of the 5½ per cent difference estimated by the author, in all cases where the boiler capacity is great enough to warrant the installation of pulverized-fuel apparatus. In conclusion, I should like to ask the author exactly what is included in the figure for "oncost charges" in Table 16.

Mr. C. Erith (*communicated*): The author has practically ignored the direct method of firing boilers with pulverized fuel, although this is the only method which is free from fire and explosion risks. I wish to call attention to the latest development in pulverized-coal firing, for which I have secured the provisional patent. Each direct-firing unit is self-contained and driven by a constant-speed motor; it draws in preheated air for drying the coal during the initial stage of pulverization. It is fitted with an air separator, which returns coarse particles, and therefore it delivers coal in uniformly fine condition to the furnace. The secondary air is preheated, as usual, in its travel through the hollow walls of the furnace. A large modern boiler uses a set of three direct-firing units, thereby assuring a complete immunity from stoppages, as two suffice for normal load. Coming now to the storage systems of pulverized-coal firing described in the paper, we learn that the only British installation is at the Hammersmith electricity supply station, which is very similar to the American systems described but has the added refinement of an air preheater. Although this London installation has been 3 years in use, no figures as to its results are furnished. Despite the enormous publicity given to the Lopulco tests of 3 years ago at Lakeside, Milwaukee, the author tells us that there are still only 9 plants, totalling 43 boilers, using the Lopulco system in America. Referring to the Milwaukee tests, we see that the normal rating of 90 000 lb. of steam was reached on only one of the five tests, when the efficiency, including economizer, was 84·6 per cent, though a dried coal, 11 per cent ash and 35 per cent volatile, was being used. This corresponds very closely to the author's definition of an ideal coal for pulverizing. The author also tells us that a further 91 boilers in 29 other plants are adopting this method, under the remarkably high normal load guarantees of 85 per cent without economizer, 88 per cent with economizer, and 89 per cent with air heater. But in the case of the Vitry plant at Paris the guarantee is only 84 per cent, including economizer, although they will use good coal of 12 600 B.Th.U.'s per lb. as fired. Regarding overload capacity, it is suggested that the greatly increased cost for the Lopulco system as compared with stoker equipment can be offset by getting higher overload capacity. Duties up to 400 per cent nominal rating, say 12 lb. actual steam per sq. ft., are guaranteed, but these can easily be equalled with stoker firing. For instance, the Riley stokers at St. Pancras Electricity Works, London, 3 years in use, can easily give 12 lb. steam per sq. ft. of boiler heating-surface, while the huge boilers of the Buffalo General Electric Co., also fitted with Riley stokers, started 7 years ago, are easily capable of 12 lb. steam per sq. ft.; whereas the Lakeside plant, with the Lopulco system, is limited to 7 lb. per sq. ft. As regards the size of boiler units, I would remind the author that he states in his "Manual of Mechanical Stokers" (page 138) that: "A typical large installation of Riley stokers is that of the Compagnie Parisienne Distribution Electrique power station at Paris, which contains 10 very large water-tube boilers, each of 22 600 sq. ft. heating surface, plus superheater and economizer, each boiler unit evaporating up to 176 000 lb. of water per hour." Returning to American practice, there are 64 central stations, totalling 3 000 000 kW capacity, now under construction; all but five of these will be stoker-fired. Among them is the huge new Kearny plant at New Jersey, where 9 Riley stokers are being installed, each capable of burning 15 tons of coal per hour on a single archless furnace.

Mr. L. M. Jockel (*communicated*): It is unfortunate

that the author has been unable to obtain more extensive data with regard to British power station practice with water-tube boilers and mechanical stokers, and consequently it would seem that the comparisons in the paper are hardly fair to present-day practice in this country, where different conditions obtain. Unless one can afford to spend a considerable time in the U.S.A. studying the applications of pulverized fuel, it is necessary to depend upon reports, such as those of Mr. L. C. Harvey and others, for practical information upon the subject, although the author does not refer to the latest report by Mr. Harvey issued by the Fuel Research Board in 1922. On page 393 the steel-tube economizer is condemned because it fails to withstand for long the corrosive action of the flue gases, but surely this is a mistake, as the trouble with this type of plant is internal corrosion, assuming, of course, that attention is paid to the temperature of the feed-water inlet. If the necessary steps are taken to prevent internal corrosion, such as de-aeration of the feed water and, in the case of high-pressure boilers, a closed-feed system and evaporated make-up, then the steel-tube economizer possesses certain advantages in practice over the cast-iron type. It is very difficult to analyse the data put forward in the paper, but the author is distinctly unfair to the majority of generating engineers when he states on page 396 that an efficiency of 80 per cent, as obtained on an abnormal test, is believed by station engineers to apply to their plant all the year round. If extensive data on present British power station practice as applied to large stations had been obtained, the value of the figures put forward would have been considerably enhanced. The data given for American power stations with mechanical stokers only serve to confirm the opinions held in this country, that the art had never reached such a stage of perfection in the United States before it was arrested by the introduction of pulverized fuel on a large scale. The data for the initial installation at Michigan are not given in the present paper, although the efficiency of 80·2 to 82·7 per cent for boiler and superheater only was at that time a fine achievement. On page 400 the author's attempts to make comparisons between Lakeside and Dalmarnock are rather unfortunate and, as the data stand at present, practically valueless to engineers with years of boiler-house experience. The figures have already been discussed in their true light, however, by one or two previous speakers. It would be interesting to learn what the author considers to be the limiting figure for the efficiency of a modern water-tube boiler plant, as various published tests have shown 89 per cent and over on the "gross or higher" calorific value of the fuel. The data put forward in Table 13 for auxiliary power consumption in mechanical-stoker plants may be true for American practice, but they are not typical of present-day practice in this country, where the figure quoted of 4·86 per cent could in very many instances include the whole of the energy used in the power station for all auxiliary purposes. In commenting upon ash troubles on page 415, the figures for the average ash-contents ejected via the chimney top and deposited in the combustion chamber are given, but no mention is made of the deposited percentage on the various heating surfaces, nor of the methods employed to clean these whilst steaming and the energy consumption and cost of such cleaning. The calorific values of fuel for American tests are apparently remarkably accurate, as the figures quoted actually include the last heat unit, indicating, of course, that the art of calorimetry has reached a state of perfection in the United States quite unknown at present in this country.

Mr. J. E. O'Breen (*communicated*): The author is not quite fair in his comparison between powdered fuel and stokers and he therefore comes to a conclusion that gives a wrong impression of the present situation. He states that pulverized fuel gives an efficiency of 86 per cent, while stokers give 81½. In this connection I would draw his attention to the fact that my firm guarantees for these very best conditions for the Pluto stoker an efficiency of 86 to 87 per cent, i.e. slightly higher than that for powdered fuel. Under ordinary conditions the efficiency will perhaps be slightly lower, due to soot on the boiler tubes, etc., but it can be maintained for stokers as well as for powdered fuel. By installing modern regulating devices as, for instance, the Hagan apparatus, it is possible to control the whole boiler house and all the mechanical stokers from one central point, so that powdered fuel has no advantage in this respect. In the case of mechanical stokers, unburnt fuel in the ash depends largely on the contents of ash in the fuel which is used, and on the melting-point of the ash. For this reason it is impossible to guarantee the same high efficiencies for coal with 40 to 50 per cent ash as for coal with 5 to 10 per cent ash. The guaranteed efficiencies for these low-grade coals will therefore be from 76 to 80 per cent. It is, of course, possible that powdered fuel will give results slightly better than this, although I have never seen tests of powdered fuel where the coal contained more than 15 to 20 per cent ash, and I am not convinced that the Lopulco system will be successful in burning these coals. In any case, the powdered-fuel system has still to prove its superiority for these fuels and for the moment I am not sure that it will even be possible to burn them. I should like to draw the author's attention to the fact that it is quite possible to obtain very favourable results when working mechanical stokers with liquid and gaseous fuels. As far back as 1910 we made extensive tests on the Continent with Pluto stokers and blast-furnace gas, the gas being used for overload and peak loads. On peak loads an evaporation of more than 10 lb. of steam per sq. ft. of boiler heating-surface was obtained. I therefore do not see the advantage of pulverized fuel as claimed by the author under Conclusion 4 on page 416.

Mr. N. Swindin (*communicated*): The discussion on the paper has not brought out sufficiently the scientific achievement of the efforts of the staff responsible for the successful application of pulverized fuel to boiler firing. Much has been said concerning the ability to build power stations in this country, compared with that available in America. This few will deny. What scientifically-trained men in this country complain of is the opportunity to carry out research on basic industrial processes on the scale that exists in America. To anyone conversant with large-scale research, it is evident that no less than £1 000 000 was spent before sufficient data could be compiled to enable the Lakeside plant of

the Milwaukee Electric Railway and Light Co. to be erected and put into commission. The success of the installation has demanded the solution of the following first-class problems: (1) The drying and pulverization of coal at an economic price and with reasonably robust plant; (2) the conveyance of powdered coal as a fluid in pipes without risk of explosion; (3) the correct designing of a burner which can be used for powdered fuel, gas and oil; (4) the manufacture of refractories to withstand the high temperature of combustion, and a design of furnace which keeps the temperature of the walls below that of fusion of the material; (5) the removal of the ash in a continuous manner, and all difficulties due to slagging; and (6) the transmission of an enormous quantity of heat at a high rate of transmission without damage to the boiler. The success of the pulverizing plant is due to the application of the best ore-crushing practice at mines, i.e. the continual screening of the product and the return of the "oversize" back to the mill. In the Lopulco system the screening is done by pneumatic means continuously: the air system being a closed circuit prevents all risk of loss and danger due to "dusting." The transference of powdered substances with air as a carrier is now a well-known process. With coal the quantity of air used must be well below that required for ignition. Ten per cent of the air required for combustion is nearly 1 000 times the volume of the actual dust, and of approximately equal weight. Thus we have practically air passing through the pipes and yet it is not sufficient to ignite the coal. As air must be blown into the furnace, the addition of the fuel adds but little extra resistance to the flow. Stanton has shown that the resistance to flow of a fluid is a function of vd/ν, where v is the velocity feet in per second, d the diameter in feet and ν the kinematic viscosity, i.e. the ratio of absolute viscosity to the density η/ρ. The viscosity of air at 20° C. is 0·000184 C.G.S. units and the density at 760 mm pressure of mercury is 0·0012 g per cm³; hence the value of $\nu = 0{\cdot}000184/0{\cdot}0012 = 0{\cdot}1533$ C.G.S. or $0{\cdot}1533/929 = 0{\cdot}000165$ ft.-sec. units. Now the addition of 1/1 000th part by volume of coal dust would not greatly affect the viscosity but it would double the density, so that the value of ν for dust-laden air would be 0·0000825. If the velocity through a 6-in. pipe be, say, 30 ft. per sec., we have for pure air

$$\frac{vd}{\nu} = 30 \times \tfrac{1}{2} \times \frac{1}{0{\cdot}000165} = 90\,900$$

and for dust-laden air

$$\frac{vd}{\nu} = 30 \times \tfrac{1}{2} \times \frac{1}{0{\cdot}0000825} = 181\,800$$

Referring to the Stanton chart* we find, taking the steel pipe line, the following values:

For pure air $mig/v^2 = 0{\cdot}003$

and $i = 0{\cdot}675 = 0{\cdot}08$ ft. of water per 100 ft. run of pipe.

For dust-laden air $mig/v^2 = 0{\cdot}0027$

and $i = 0{\cdot}6075 = 0{\cdot}1458$ ft. of water per 100 ft. run of pipe,

where m = hydraulic mean depth,

and i = hydraulic slope (head/length).

* N. Swindin: "Flow of Liquid Chemicals in Pipes" (Benn Bros., Ltd.).

With coal as a powder and already mixed with 1 000 times its volume of air, when it passes through the nozzles of a burner it is almost like a gas. The burner is therefore quite a simple piece of apparatus, the flattening of the nozzle enabling the surface to be increased for combustion with the secondary air. The design of the combustion furnace embodies points which the practical man would reject at once. In the first place it is large enough to enable combustion to be completed. The preheating of the air performs two functions: it reduces the temperature of the inner surface of the furnace below that of the actual temperature of combustion and below that of fusion of the material, and it diminishes enormously the loss due to radiation from the outside surface of the furnace; in addition, combustion is assisted and is completed in less time. The life of the brickwork shows that greater attention is paid to refractories than is usual in this country. The treatment of the ash is really a trick. The water screen operates by sudden cooling of the ash slag, so that strains are set up in the slag similar to that in the Rupert's drop, causing the stuff to fly off in a granular form. Besides this, these tubes lying at the bottom of a fierce radiant chamber prevent much loss of heat. The amount of heat absorbed by this screen must be considerable. The chief feature of the furnace, however, is the enormous rate of heat transmission to the boiler tubes. It is usual to express this as so much evaporation of water per sq. ft. of heating surface per hour. Taking the author's figure of 14 lb. of water from and at 212° F. per sq. ft. per hour, we get the enormous figure of 155 kilogram-calories per m² per hour per mean temperature difference between the fire temperature and the temperature of the water in the tubes. This figure is calculated as follows:—

The exact furnace temperature obtained with powdered fuel has never, so far as I know, been ascertained, but I should say that it is at the very least 2 500° F. A furnace temperature of 2 100° F. is given in the paper for a mixture of powdered fuel and blast-furnace gas. Taking, therefore, the fire temperature of 2 500° F., the temperature of the gases leaving the boiler at 430° F., and the temperature of the water from the boiler at 417° F., the mean temperature difference θ_m is found by Grashof's formula thus:—

$$\theta_m = \frac{\theta_1 - \theta_2}{\log_e(\theta_1/\theta_2)} \quad \text{(see Fig. A)}$$

$$= \frac{2\,083 - 13}{\log_e 180}$$

$$= \frac{2\,070}{5{\cdot}187} = 400^\circ \text{ F.} = 222^\circ \text{ C.}$$

$$K = \frac{H}{\theta_m}$$

where H = cals. per m² per hour,

and K = coefficient (cals. per m² per hour per deg. C. difference).

Therefore $K = \dfrac{14 \times 10 \times 537}{2{\cdot}2 \times 222} = 155$

In B.Th.U.'s per sq. ft. per hour per deg. F. difference, $K_1 = 155/4{\cdot}5 = 33{\cdot}4$.

The following values of K have been obtained by similar calculations from representative practice of various types of boilers: For the ordinary Lancashire boiler as ordinarily fired, 20; for a Babcock boiler, 40; for a Bonecourt boiler fired by ordinary coal gas, 80; for Nicholson's experimental boiler, 120; and for the powdered-fuel boiler described in the paper, 155. A careful study of the transfer of heat through plates from hot gases to liquid by conduction shows that it is impossible to obtain anything like this figure except at velocities beyond all practical value. Nicholson's experimental boiler which was designed to increase the rate of transmission by increasing the velocity of gases past the heating surface in accordance with Reynold's law, did not accomplish the rate described in the paper. Only by allowing the radiant heat to flow without hindrance to the boiler can such a transmission be obtained. It is noteworthy that Mr. Stromeyer in a recent paper discussing "The Principles of Boiler Design," dealt with the necessity of screening the boiler surfaces from the radiant energy in order to prevent damage. To one who has long been engaged in studying the mechanism of heat transfer in difficult processes of chemical manufacture, it would appear that the Lopulco system of boiler

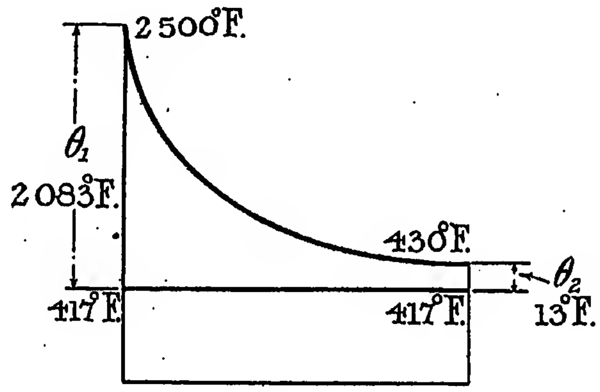

FIG. A.

firing has accomplished most of what modern science has to say on the subject. Improvements may lie in the region of burning the coal mixture under pressure in order to increase the density of the gases in the furnace. In comparing the advantages of the powdered-fuel combustion system with mechanically operated furnaces the size of the modern boiler has put the latter entirely out of court. The Lopulco system marks only a beginning of the real study of the best way to make steam on a large scale.

Mr. E. Kilburn Scott (*communicated*): The most striking piece of evidence of the success which pulverized coal has gained over stoker firing is at the Colfax power station, Pittsburg. This station is situated about a mile from a coal mine owned by the same financial group and it has plant units of 60 000 kW each. When they first started about five years ago, each boiler was fitted with a mechanical stoker and everything was done and every instrument connected up to make the boiler plant as perfect as possible, and it was operated by expert engineers. It is therefore all the more significant that within a few years the consulting engineers and the chief engineer of the power house, and also the financiers who are behind the huge organization that controls Colfax, have been converted to the use of pulverized coal, and the 60 000 kW unit now in hand will be worked on that system. It would have been easier to continue with mechanical stokers, but the decision to change was made after a thorough investigation had been made of what pulverizing had accomplished elsewhere; that is to say, it was not made merely for the sake of change, but from a real conviction. Our boiler-house practice has been in a rut for years and I fear that this is partly due to the habit into which some consultants have got of letting boiler-making firms dictate to too great an extent. Also I am afraid that some of those in charge of power houses know more about electrical apparatus than about boilers and how to burn fuel economically. Yet it is the boiler houses that require the most watching; it is there where supervision is most required and where much of the money goes. Carbon has for years been wasted in riddlings and in clinkers, but the waste has been condoned, or perhaps in some cases not known about, and many who knew have suppressed the fact. The advent of pulverizing will change all that and I believe that the competition will be a good thing for the whole industry of electric power generation. In order to reduce loss of carbon in the ash pit some power station engineers go out of their way to purchase fuel with a highly fusible ash, and select coal in sizes that give low losses by riddlings. Pulverizing does away with all that; station engineers can forget all about low-fusibility ash and sulphur and burning of grate bars, and size of fuel, and need not bother much about volatiles. All fuels are alike when resolved into minute particles, for so long as the particles are given sufficient air in a large enough combustion chamber they will burn satisfactorily. The large combustion chamber has been criticized, but I think that it is well worth the expenditure involved and extra building space, since a greatly increased radiating surface is obtained. Most of the evaporation of a boiler is due to radiant heat waves impinging on the first tubes, and the method of having a screen of tubes at the bottom of the combustion chamber is excellent because it absorbs the radiant heat that goes downwards. Another criticism is that the temperature is so very high, but surely that is all to the good and it is in the right place. By building the combustion chamber of sufficient size and using air flues on the walls and a water-tube screen at the bottom there is no trouble with brickwork. In French practice the composition of the firebricks used is suited to that of the ash of the coal, and in this way slagging of the firebricks is prevented. The much greater size of the combustion chambers of the two new boilers at Hammersmith as compared with the first boiler is very striking. The two burners are 23 ft. from the bottom of the combustion chamber in each of the new boilers, whereas the four water-cooled burners of the first boiler are only 12 ft. from the bottom. Much has been said about the fineness of the ash which results from pulverizing, but a demand is springing up for the very fine ash and I understand that as much as 10s. per ton has been offered for it, and for a good reason. It will be a rather strange position if later on it is found to be a commercial proposition to burn low-grade material partly for the purpose of getting more fine ash to sell.

Mr. J. D. Troup (*communicated*): The author has hardly done justice to himself or to pulverized fuel by emphasizing thermal efficiency to such an extent. In the first place, no comparison between pulverized fuel in America and mechanical stokers in Britain is possible on any common basis, because the fuels are different. In any fair comparison the same fuel should be used in each case. Would the author expect to get Milwaukee results if Dalmarnock coal were used? There is, however, a great deal more to be said for pulverized fuel than merely to claim for it a higher thermal efficiency. We should expect a higher thermal efficiency when using coal in a powdered form, and there can be little doubt that it is attained in practice. A close inspection of the paper shows, however, that there are other advantages in using pulverized coal, some of which may be even more important than securing a higher thermal efficiency. One of these advantages is simplicity of combustion control, and this point becomes one of greater importance when industrial plants are considered, because the skill of the boiler staff is generally not so high as that customary in large power stations. It is necessary also to look ahead in these matters. The boiler unit is already a huge affair, and mechanical stokers on a large scale become a very cumbersome arrangement in the combustion chamber, when the alternative is simply a series of Bunsen-type burners; and if a larger furnace is required it becomes a simple matter of adding burners. Incidentally, the Ford system of centralized control is a significant sign of the times, following the modern movement of all our industrial and business organizations. It would probably be impossible to operate such control with any fuel except that which could be used in some form of burner. Can the author give any indication of the saving in labour effected by such central control?

Mr. J. A. West (*communicated*): I have read the paper with great interest and I regret that in such a lengthy paper the author has dealt only with the Lopulco system. This, I presume, is owing to the fact that he is only dealing with the comparison of the Lakeside and Dalmarnock installations. In this country we have the Holbeck system, which is installed at the Hammersmith Borough Council electricity works referred to briefly in the paper. The first portion of this plant was put in operation in November 1920, so we can really be proud of the fact that the possibilities of pulverized fuel for steam raising were appreciated in this country almost as soon as in the United States. From personal experience I know that the plant at Hammersmith has more than justified its installation and that the Council has been amply rewarded for its progressive policy. Probably in the near future, figures will be available regarding the performance of this plant which, I venture to state, will be found to equal those obtained at the Lakeside installation. Probably one of the main factors that have delayed the use of pulverized fuel for steam raising in this country has been the nominal low price of coal, and no doubt it has been considered that the cost of preparing the fuel for powdered-fuel firing was not compensated for by the efficiency gained. There are, however, many other factors to be taken into consideration which do not warrant hasty conclusions. The power taken for pulverizing and distributing the fuel to the boilers must be credited by the power taken by mechanical stokers. Coal-handling, operating and maintenance costs, capital expenditure, etc., must all be reviewed. There is also another point worthy of consideration, particularly in generating stations, viz. the fact that the pulverizing could be carried out during off-peak periods, thereby reducing the cost of preparation of the coal, as a very much reduced power rate would be in operation. With regard to the author's remarks on the explosion question, I thought that this bogy had, once and for all, been laid by the heels. My personal experience is that with ordinary care there is no more risk of explosion from a modern powdered-coal plant than that existing in a well-designed fuel-oil system. I should like to ask the author if he can state how long the water screen in the furnace has been in operation, and also if any difficulties have arisen in connection with it. Personally, I have found that by admitting air at the bottom of the furnace a result similar to that claimed for the water screen is achieved. I do not quite agree with the author's statement that with mechanical stokers a coal changing from 12 000 to 9 000 B.Th.U.'s would mean a fall in output of 50 per cent and also a fall in efficiency of 10 per cent. This, in my opinion, would only occur where draught was limited and where badly graded coal of very low volatility was being used. With a good ash-handling plant little trouble would be experienced with the ashes. The author's figure of 5 per cent gain in efficiency with pulverized fuel over the best-equipped mechanical stoker is, in my opinion, a correct one, the gain being obtained with a higher proportion of CO_2 and reduced loss in the ash. It may be possible with a few coals burnt on mechanical stokers to have a very much reduced ash loss, but this is rather the exception than the rule. It is incidentally mentioned in the paper that the successful adoption of pulverized fuel for steam raising has necessitated further improvement in mechanical stokers, as manufacturers are being menaced more and more by pulverized-fuel competition, and I agree with this view. An increase in efficiency of 5 per cent with pulverized-fuel firing would effect a saving of 1s. in the £, from which one would naturally conclude that, with coal costing under £1 per ton, the cost of preparation would not be justified, but, as previously mentioned, there are so many factors entering into the case that deeper investigation is necessary for comparison before deciding what would be the most economical plant to install. From a purely coal-conservation point of view, pulverized fuel is the only system and, in conjunction with low-temperature carbonization plants, we should be taking full advantage of the valuable products that our country offers. Engineers should give very serious consideration to the whole question when installing new plant.

[The author's reply to this discussion will be found on page 460.]

Mersey and North Wales (Liverpool) Centre, at Liverpool, 10 December, 1923.

Mr. J. Hamilton: I should like to ask if the Lopulco system is the only one at present developed which overcomes the slagging difficulty, and if it can be depended upon to do this consistently when dealing with the varying fuels used in this country, which are mostly in the form of slack. I am in agreement with the author's statement on page 400 in regard to the lack of combustion space in our present-day mechanically fired boilers, and I think that it is fairly common practice nowadays to add moisture to the coal as fired to enable combustion to be completed before the fire reaches the ash doors. This is often difficult to ensure while maintaining the output from the boiler, due to variation in the fuel. I assume that feed-water regulators are in use on the boilers in conjunction with automatic control on the feed pumps at the River Rouge plant. Table 9 is interesting but is apt to be misleading. In considering the claims of pulverized fuel, the cost of labour is one of the largest items from the operating point of view, and the number of men required to operate the plant must be taken into consideration. In the table the author gives a total of 86 men for boiler room and pulverizing house, with a total number of hours worked of 11 554, which gives an average of approximately 134½ hours per man per month. I understand that labour is much more "flexible" in the United States than in this country, and it would be interesting to know how this total of 86 men would compare with, say, the number of men necessary for a similar plant in this country, each man working 48 hours a week on his own particular duty in connection with the plant. I assume that the figure includes the men on repairs and maintenance, as otherwise it appears unduly high compared with the total of 84 on operative work at Dalmarnock, where this figure includes turbine-room operation also. With reference to the wear and tear of brickwork mentioned in the paper, I should be glad if the author would say whether carborundum bricks have been tried and, if so, with what results. One would have thought that no soot would be formed by the combustion of pulverized fuel, but I notice that soot blowers were fitted to the boilers shown on the lantern slides and I take it that they are fitted to deal with lodgments of fine ash. Can the author say if any attempt has been made to reduce the ash from the chimney by centrifugal action of the gases at the base of the chimney? It is stated on page 417 that the ideal coal for pulverizing contains from 33 to 40 per cent of volatile matter, and on page 418 that pulverizing lends itself particularly well to low-temperature fuels containing from 8 to 12 per cent of volatile matter, and it would therefore appear that practically any fuel is suitable and may be used in pulverized form. If this is so, and burners are now designed with an adjustment to cover all conditions efficiently, a point has been reached beyond the range of mechanical stokers. One of the chief essentials in maintaining a continuously high boiler efficiency is to keep the plant up to a high standard of overhaul and cleanliness, and difficulty is experienced on old plants where there may be a large number of small units all in service at times of heavy demand. A higher efficiency can be expected from a modern lay-out, especially in its earlier days.

Professor G. E. Scholes: It is evident that furnace design has been given very careful consideration in the paper, and one outstanding feature of the boiler installations mentioned has been the cubical capacity of the furnaces used. Believing that large furnaces tend to increase the boiler efficiency, I calculated the amount of pulverized coal burned per cubic ft. of boiler furnace in 11 plants now being installed in America by the Combustion Engineering Corporation. The boilers are of several different makes and the average furnace volume per boiler horse-power rating is 5·6 cubic ft. At Cahokia the furnace volume per boiler horse-power is 7¼ cubic ft. Assuming that the normal load on the boilers is equal to a 300 per cent rating and that the evaporation from and at 212° F. per lb. of coal is 10 lb., the average coal burned per hour per cubic ft. of furnace volume in these boilers is 1·84 lb. The author's figure of 1 cubic ft. of furnace volume per 3 lb. of coal burned per hour is thus a conservative one, and the tests given on page 404 in connection with the Lakeside station show 1·39 lb. of coal burned per hour per cubic ft. of furnace volume when the boiler is working on a 215 per cent rating. Boiler manufacturers in America using mechanical stokers are increasing the volumes of their furnaces, and three recent installations show that the rate of burning coal is respectively 2·33, 2·0 and 3·37 lb. per hour per cubic ft. of boiler furnace with the boiler working on a 250 per cent rating. Can the author give similar figures for large boiler installations in this country similar to that of the Dalmarnock station? He has pointed out the great importance attached to the provision of a water screen in the base of the furnace, and it is evident that with the high furnace temperatures involved—which are probably of the order of 3 000° F.—the question of refractory material for furnace linings is of great importance. At the Cahokia station at St. Louis, water screens are used in the front and rear of the furnace in addition to the bottom, and Foster radiant superheaters are being fitted to the side walls of the furnaces in two of the boilers. By these means it is hoped to lengthen the life of the furnace linings by reducing the temperature in the locality of the screen and superheater tubes. Can the author say whether the maximum amount of moisture of 2 per cent which is allowable is adherent or inherent? I gather that the coal is crushed to pass through a ¾-inch ring, and is then taken through a vertical drier. It does not seem likely that the inherent moisture would be affected by this process. The author refers to the high efficiency obtained by the Edgemoor 4-pass boiler, and suggests that this efficiency is probably due to the gases passing the tubes four times. It is interesting to note that the latest Edgemoor boiler is a baffleless single-pass boiler, and that very high efficiencies are anticipated. Pressures in steam boilers

are increasing rapidly; some American boiler manufacturers market boilers for working pressures of 600 lb. per sq. in., and designs are in hand for pressures of 1 200 lb. per sq. in.

Mr. F. R. Maxted: In considering the case of pulverized fuel, I have chiefly concerned myself with the question for and against adopting the system in this country on plants now working with mechanical stokers. It seems to me that the first point of importance lies in the price at which a suitable fuel can be purchased. A recent quotation which came to my notice for coal, suitable in every way for powdered fuel, was 9s. 3d. per ton. What will be the price of this fuel in a year or so's time when a demand has been created for it? A particular boiler plant in which I am interested is to consist of six Babcock boilers, four of which are now installed, and these will presently consume 100 tons of coal per boiler per week, i.e. 500 tons of coal per week on five boilers working out of the six. The fuel to-day costs 21s. 7d. per ton, and, on account of the heavy duty on the boilers, it has not been found possible to use a cheaper-grade coal, nor does it seem likely that we shall be able to do so in the future. I have taken this particular plant and examined the cost of installing coal-dust firing and the economy that would result. The boilers are fitted with every modern appliance and instruments for the scientific control of the boilers and continuous testing. On week-in, week-out tests, the average efficiency of the plant is 75 per cent, and when it is considered that the average boiler plant in the country has an efficiency, as the author has told us, of just under 60 per cent, it would not at first appear that a case could be made out for powdered fuel. The chimney issues black smoke at intervals and gases pass away at 400° F. There is a loss on the refuse heap equivalent to 5 per cent of the fuel fired, which amounts to a loss to the ash heap of 1 300 tons of coal per year. The labour in the stokehold to-day on the four boilers is from two firemen per shift, and I estimate that with coal-dust firing this labour can be halved, thus saving approximately £400 a year. The type of coal grinder selected as being most suitable is the turbo-pulverizer manufactured by the Powdered Fuel Plant Co. This machine appears to be the lowest in first cost, occupies very little floor space and cuts out the heavy initial cost of coal driers, magnetic separator and fan. One of these machines would be installed on each boiler, and the power required to operate them would be 25 h.p. per machine. After adding the cost of grinding to the price of the fuel, adding 3d. per ton for maintenance and deducting 10d. per ton, which is the cost of running our existing mechanical draught, and assuming that the 9s. 3d. per ton mentioned above would probably be increased to 12s. in the course of time, allowing for grinding, etc., the cost at the boilers on this same fuel would be 14s. 3d. per ton. On a basis of heat units per 1d., we have the following comparison: To-day we obtain 106 000 B.Th.U.'s per 1d. on stoker firing, and with coal dust, the cost, after allowing for grinding, etc., works out at 1d. per 123 000 B.Th.U.'s. Assuming an 80 per cent efficiency, and allowing 10 per cent for interest and depreciation, the saving in favour of coal dust works out at £4 700 per year, and pays back the cost of alterations in approximately 1 year and 9 months. A few days ago I had an opportunity of inspecting two Babcock and Wilcox boilers, each of a capacity of 30 000 lb. per hour, fitted for burning coal dust and blast-furnace gas. This plant was fitted with one turbo-pulverizer, which supplied fuel for the two boilers. On the firing floor there was not the least appearance of coal dust or coal, and one man only was in charge of the complete plant. The iron content of the blast-furnace gas had the effect of fusing the ash, which fell to the bottom of the combustion chamber as a molten slag. I was told that the cleaning out of this slag was done at week-ends only, when there was a layer of about 12 to 14 in. There was said to be no difficulty in breaking this slag up and removing it. From Monday morning to Saturday night no labour was employed other than the one man mentioned. The turbo-pulverizer machine had been in use for two years and had given no trouble. The whole appearance of the plant was most pleasing, and it was very easy to control. The turbo-pulverizer made very little noise and seemed to have practically no vibration. There was no smoke at the chimney except a light grey vapour which was lost to view at about 10 ft. from the chimney top. The chief points in favour of coal-dust firing seem to me to be: (1) The ability to burn a low-grade fuel; (2) the ability to follow fluctuations of demand; and (3) the elimination of arduous work on the part of firemen, entailing extreme physical fatigue. In regard to the type of pulverizer selected for the 6-boiler installation referred to, it is probable that a central grinding plant would make the change-over too costly to be considered, and, in addition, it is probable that a case for coal-dust firing could only be made out for this particular job when employing a cheaper-grade fuel.

Mr. G. P. Dennis: I have been following with interest a pulverized-coal system manufactured in Liverpool which does all that the Americans claim to do, but with less initial expense and with lower operating costs. This method is known as the Buell system and possesses several novel features. It comprises a special burner which enables a very low grade of fuel to be used. The burner is a marked advance on any other, because it enables the operator to obtain such an intimate mixture of air and coal that any grade of fuel can be efficiently burned, and, at the same time, the length and shape of the flame can be changed as desired. This flame control enables a much smaller combustion chamber to be used than that required in the United States. A further advantage is that the Buell electric control automatically regulates its own steam pressure. When the correct head of steam is raised, the flame is regulated so that a constant pressure is maintained. Sudden demands for increased pressure are instantly met, and it is possible to work the boiler at 100 per cent overload. It is possible with this system to use lignite—an extremely low-grade fuel—on a Cornish boiler. In Australia this system is more successful than any other, and four Babcock and Wilcox boilers with a normal capacity of 1 425 h.p. are now successfully running in Melbourne. The

difficulty of the successful pulverization of coal with a low power factor has already been solved by the use of the Buell-Milloyd unit, which works at the low grinding cost of 7 kWh per ton ground, while its life is considerably longer than that of American pulverizers used for this purpose. While America has made considerable progress in the adaptation of pulverized coal, I am glad to say that England is in no way lagging behind in the manufacture of efficient apparatus for burning it.

Mr. H. W. Hollands: I feel that there is very little left to say regarding the principles of powdered-coal firing, but on many points I cannot agree with the author's application of those principles. I am convinced that the unit system is the only one worthy of consideration in this country. The author states that he has not included any reference to this system because "in the first place this is more applicable to smaller boiler plants and not so much to large power station work, while general furnace work is also disappointing." I would ask members to bear in mind that it is nearly impossible to make any sort of useful comparison between the power stations of America and those of this country, but there is no power station in Great Britain, either built or contemplated, to which the unit system could not successfully be applied. At the present time there are running, on boilers alone, 160 turbo-pulverizers burning a total of 146·2 tons of coal per hour, while for furnaces the figures are 288 and 92·1 respectively. It may therefore be agreed that this system has certainly gone beyond the experimental stage and has, in fact, taken a much greater hold on engineers in Europe than has any other form of central station firing. The author states that with crushing or grinding mills of the Fuller or Raymond type the coal has to be dried down to at least 2 per cent and preferably 1 per cent of moisture. With the unit system it is easily possible to use coal containing 8 per cent moisture, while, by passing preheated air through the machine with the coal, moisture contents as high as 15 per cent have been dealt with. In an article in the *Iron and Coal Trades Review*, February 1922, under Mr. Brownlie's name, it was stated that "if coal can be pulverized without drying it would be an enormous improvement, but up to the present time it has always been considered necessary to dry it to within 1 per cent moisture—a formidable operation for most coals." I am in entire agreement with this view. Driers are, at the best, costly additions to a plant; they are inefficient and are, on account of their great radiant heat, unpleasant to work near. With any form of central station practice or, in fact, with any system which stores powdered coal, there is a very real danger of explosion or spontaneous combustion, and a number of appalling accidents due to these causes have taken place in America. As the author points out, the risk has now been largely overcome, but this has entailed special bunkers, special buildings, and altogether considerable unnecessary expense. With the unit system the coal is burnt as it is pulverized; none is stored and there is therefore no possible risk of fire or explosion. The author deals very fully with the ash-slagging question, including the water screen designed to overcome any such trouble. Such a screen is an unnecessary luxury, since a proper design of combustion chamber will always result in the ash being deposited in a perfectly dry state. At Hammersmith Corporation Electricity Works—where three boilers burning powdered coal are evaporating 130 000 lb. of water per hour—no trouble due to ash slagging has been experienced, and the same remark applies to almost every unit plant in the country. The combustion chamber should be so designed that there is a vacuum at the base, balanced pressure in the middle zone, and a slight plus pressure at the first pass. The ingoing cold air cools the ash and prevents the formation of slag. It might be suggested that such an arrangement would lower the efficiency of the plant, but that this is not the case is convincingly shown in the two following extracts taken from recent tests on boilers fired by means of turbo-pulverizers. The first is a Babcock and Wilcox boiler having a heating surface of 5 760 sq. ft. and which, using a coal (Durham splints) having a calorific value of 9 550 B.Th.U.'s per lb., has been running with a constant overall efficiency of 83 per cent. The second case is also a Babcock and Wilcox boiler with a heating surface of 2 690 sq. ft. and which, using a coal having a calorific value of 10 788 B.Th.U.'s per lb., has been running with a constant overall efficiency of 86 per cent. In dealing with the troubles due to wear of brickwork, the author makes little or no reference to a point which, to my mind, is of the highest importance, i.e. the velocity of the powdered coal in the pipes and through the burner. Most of the early troubles were due to too high velocities, the result being serious impinging on, and consequent scouring of, the brickwork. That fact has now been recognized and it is not uncommon with unit pulverizers for a plant to run for 18 months without any repairs to the brickwork being required. To sum up, I would say that, while the unit system is giving results quite as good as those obtained on any other system, the difference in cost is enormous, the space occupied is very considerably smaller, while the risk of fire or explosion is entirely eliminated.

Mr. R. G. Devey: The author refers to boiler plants in this country working at 60 to 70 per cent efficiency. I venture to say that what is required is not altogether the installing of pulverized-fuel plant but the introduction of scientific control on the boiler plants which are working to-day. I should like to ask the author how he proposes to deal with the present boiler plants. A number of new ones having recently been put down, does he suggest scrapping these to make room for pulverized-fuel boiler plants? Assuming that with mechanically fired boilers the efficiency is from 78 to 80 per cent, to scrap existing plants would mean providing a sinking fund and adding interest at the rate of 5 per cent to the working cost if the pulverized system were introduced. It appears that to obtain a higher efficiency equal to, say, 85 per cent the saving in fuel would hardly warrant the scrapping of existing mechanically fired plants which are at present scientifically controlled. If this is so, then pulverized plants are a good proposition only when a new installation is

being put down. In comparing American and British plants, it is rather unfortunate that the author had to deal with plants having load factors of 60 and 34 per cent respectively, as a low load factor cannot compare with a high one on boiler plants. I should like to suggest that for boiler plants the steam load factor should be compared and not the power station load factor, as there are a number of variables in the power house which differ in efficiency, such as turbines, generators, vacuum, water temperatures, etc. I should be glad if the author would state if suitable furnace linings are obtainable in this country to withstand high temperatures.

Mr. E. Moxon: The paper is of great value to power station engineers, particularly as it has been presented at a time when everyone is striving his utmost to obtain the highest possible efficiency in the generation of electricity. The past few years has seen an enormous advance in the demand for electricity for all purposes, and to cope with this many generating stations of large capacity have been designed and put into commission, whilst a large number of the old generating stations have been modernized or enlarged. Although very large boiler units have been erected, with the adoption of higher pressures and temperatures the method of firing the coal has been chiefly by means of mechanical stokers. It is somewhat astonishing that more stations have not equipped at least an experimental plant using pulverized coal for firing purposes. One can, however, quite understand that the smaller station requiring extensions of its boiler plant hardly dares to adopt pulverized-fuel equipment, on account of the capital expenditure involved being greater for this type of equipment than for mechanical stokers. Furthermore, the small amount of data available from independent and unbiased sources has perhaps tended to impede progress in the direction now recommended by the author. The engineers of smaller electricity undertakings have to be very careful that any plant that they adopt must be reliable and capable of giving regular service when required, and this view might even outweigh the advantages of more modern plant able to give a higher efficiency of a few per cent, chiefly on account of the fact that smaller stations have not, as a rule, the amount of spare plant that larger stations have. Again, later additions of plant are generally larger units, which often constitute a fairly large percentage of the total equipment; hence the necessity for the utmost reliability of the later units installed. Referring to the efficiency obtainable, a small generating station can to-day, with coal costing 17s. per ton delivered, generate 1 kWh for, say 0·23d., with a 20 per cent load factor, the steam generating plant having an all-the-year-round thermal efficiency of over 12 per cent, i.e. on units generated. One is inclined to think that on account of the extra expenditure involved in obtaining a very slight increase in the thermal efficiency of the steam-raising plant, given equal expenditure on other sections of the undertaking, the financial gain would be greater from a commercial point of view. I am rather afraid that firing pulverized fuel will, unless the draught is very carefully regulated, result in the emission of fine particles of dust and grits from the chimney, and I know from experience that this can be, in the case of mechanical firing of very fine fuel (commonly called "dant" or pit-heap coal), a great nuisance to neighbouring properties. Dust or grit extractors are not very effective, but perhaps the more common use of pulverized fuel has brought in its train an efficient remedy. My personal opinion is that the greatest value could be obtained by using pulverized fuel at generating stations close to large collieries for making use of the "dant" from coal washeries and pit-heap coal that has been deposited at the pit head for years, and any other low-grade fuel that may be available. This should be purchasable in large quantities at very low rates, and as the transport charges would be almost negligible the coal costs per unit would be very low indeed. Furthermore, the dust problem would not be of any consequence. I consider that the very great overload capacity of a boiler fired with pulverized fuel, stated in the paper to be 100 per cent, taken in conjunction with the speed at which a boiler so fired can be brought into and taken out of action, will make the use of a certain portion of the boiler equipment of this class of great value to meet peak-load requirements. I should like to ask the author whether the efficiency figures given for stations using pulverized fuel are calculated on the weight of fuel fired as dried or on the weight received in the bunkers.

Mr. E. W. Hall: I should like to ask the author if he has any knowledge of the pulverized-fuel system being applied to marine practice, and if, in his opinion, its adoption would entail alteration to the existing boilers, whether of the Scotch or of the water-tube type. Also, does he think that the noise caused by the operation of the pulverizers would make the system unsuitable for passenger liners?

Mr. A. E. Malpas: In the latest practice the vertical-louvre type of drier is adopted. I take it that the moisture evaporated from the crushed fuel escapes with the chimney gases. The temperature is supposed to be continuously maintained at 215° F. in order to drive off the hygroscopic water, leaving about 2 per cent combined water which can only be driven off at a somewhat higher temperature. Should the temperature rise above 215° F., however, there will be some tendency for volatiles to be driven off and so lost in the chimney, and I should like to know how the temperature is controlled.

Mr. H. S. Rowe: Many of the advantages claimed for pulverized fuel are as much due to scientific control as to the fuel itself. As the accuracy of the author's figures for the average efficiency of steam generation in this country and elsewhere have never been seriously disputed, it is interesting to note—in regard to the statement made at the foot of page 397 as to the efficiency of water-tube boiler plants—that an increase in the average efficiency of 70 per cent to the attainable efficiency of 80 per cent would result in a saving of one-seventh of the total fuel consumption. In a plant consuming 300 tons per week this would represent a saving of about 2 200 tons or, say, £1 700 annually. Such a result demands close and accurate attention and will justify the payment of £500 per annum to

a suitably qualified engineer who would obtain it, although this is a proposition which many owners of boiler plants would not consider. High efficiencies are claimed for other methods of steam generation. As much as 88 per cent is claimed for steam generation on marine boilers fitted with forced draught and air preheaters, and I should be glad if the author would state if he has any knowledge of such a figure being actually obtained. No claim was made in this case for using poor quality fuel, such as is frequently made by advocates of pulverized fuel. In spite of such claims made on page 389 and elsewhere, it will be noted that the guarantees quoted on page 396 regarding the Vitry installation do not refer to low-grade fuel, whilst the fuel used in the Dalmarnock station (see page 399) is of a quality inferior to that used in the tests on the Lakeside plant (see page 404). There seems to be some divergence of opinion as to the best size of combustion chamber required for use with pulverized fuel. This is evidenced even in the paper itself, as figures given on page 404 indicate that about 1·62 lb. of fuel are fired per hour per cubic ft. of combustion space at normal working, whereas on page 400 it is stated that 3 lb. of fuel are fired hourly for each cubic ft. of space, whilst on page 407 the description of the River Rouge plant shows that about 1 cubic ft. per lb. of coal per hour is required, assuming that the boilers relied entirely on coal. The amount of power required for pulverizing is claimed to be exceptionally low and, although in the case of the Vitry power station the power consumption is guaranteed not to exceed 1 per cent of the steam production, this involves the production of power at an expenditure of 1·15 lb. of coal per kWh, an exceptionally low figure. From the figures quoted on page 400 it would appear that the total power consumed at Dalmarnock station is between 4 and 5 per cent of the total amount generated, and although on page 397 the author states that 1·5 per cent of power is used as an auxiliary to the production of steam in the most efficient boiler plants, yet the figures quoted on page 401 show that in one case 9 per cent and in another case 4·3 per cent of the power generated at Dalmarnock is consumed in the boiler house during test periods. The figures quoted on page 405 for losses in unburnt fuel in ashes can only be described as illustrative of the general carelessness in these matters, and the Dalmarnock figures quoted on page 401, showing only 1·07 per cent loss in this respect, demonstrate what can be done with care, this figure being less than the 2 per cent quoted by the author as being the best stoker practice. Whatever may be the thermal efficiency of steam generation it is the ultimate aim of engineers to produce steam as cheaply as possible. From the figures quoted on page 416 the average cost of the fuel used works out at between 26s. and 27s. per English ton, and steam is then produced with pulverized fuel at a cost of about 21·2d. per 1 000 lb. The cost of steam at Dalmarnock, arrived at from the figures given in Table 16, may be fairly estimated, after allowing 20 per cent for capital charges, as about 19·26d. per 1 000 lb. At a local power station and a factory steam is produced at a less cost than at the American plant mentioned, and it may be that the heavy charges for fuel and labour in America make it worth while to follow up the small higher efficiency obtainable from pulverized fuel in order to reduce steam charges to a minimum. The author has made out a case for the careful attention by British engineers to the claims of pulverized fuel where heavy demands for steam are to be met.

Mr. E. Cook (*communicated*): Whilst the author has undoubtedly made out a good case for pulverized-fuel stoking, considerable improvement could be made on existing mechanical stoker plant efficiencies, without entailing additional capital outlay, by a closer supervision and a greater appreciation of boiler plant economics by the engineers in charge of steam-raising plant. The figures quoted of the Dalmarnock station were obtained under a very complete system of record keeping and testing, indicating the close attention to details which is absolutely necessary. The fact that figures approaching those of Dalmarnock are not obtained on the average station to-day with mechanical stoker plant is, in my opinion, largely due to inattention to the above-mentioned points of testing, record keeping (with the intelligent use thereof) and details of firing. If a station of average capacity, say 10 000 to 20 000 kW, is to-day operating, with mechanical stoker plant and an average calorific value of fuel of 9 500–10 500 B.Th.U.'s, at a boiler-house commercial efficiency of less than 75 per cent, then there is something radically wrong either with the plant or its operation. The author's main arguments appear to be based upon stations of large capacity. The majority of engineers are, however, probably interested in stations of medium capacity, say 10 000 to 20 000 kW, and the question arises as to the advisability of installing pulverized fuel plant in such stations. If a figure of not less than 75 per cent commercial efficiency can be obtained—and it certainly ought to be on such medium-capacity stations—can the additional 5¼ per cent efficiency be obtained by pulverized-fuel plant, and is the capital expenditure and maintenance warranted? On the other hand, is it not a better proposition to operate existing plant more efficiently by expending a portion of this outlay on efficient apparatus and continuous technical supervision of boiler-house operation? This would undoubtedly produce a definite return, whilst the installation of pulverized-fuel plant, unless accompanied by the necessary efficient apparatus and supervision already mentioned, might conceivably yield no return at all. In Table 5 the author quotes a calorific value of the coal as fired of 9 905 B.Th.U.'s, with an ash content of 12·74 per cent of the total coal. This seems to be an abnormally low ash content for such a calorific value, and unless the coal contains an unusually high percentage of moisture it seems difficult to account for the discrepancy. The foregoing remarks are based on the assumption that the plant is a modern one of the ordinary type met with in medium-capacity central stations, without air-heating and with a station load factor of, say, 35 to 40 per cent.

[The author's reply to this discussion will be found on page 460.]

Scottish Centre, at Glasgow, 11 December, 1923.

Mr. R. McLaren: The paper is the best summary of the position of the operation of pulverized fuel that we have had since Mr. Harvey's Report to the Fuel Research Board in 1919. I propose to confine my remarks to one or two of the more important points in the paper. As regards thermal efficiency, the author can hardly expect us to accept the figures given in Table 2. If they were correct, it would reflect more on those operating the plants than on the plants themselves. On the other hand, the efficiencies given for pulverized-fuel plants are based on one of the most scientifically operated stations in the world. It is futile to compare such a plant with a badly run station which happens to be served by mechanical stokers. It is stated in the paper that the efficiency of the Lakeside station is, year in and year out, 85–86 per cent, and a figure of even 89 per cent has been attained. The author very justly draws attention to the great difference that exists between the results obtained in day-to-day working and those obtained on test. If he can get 85–86 per cent efficiency in day-to-day running, why is it that only 84 per cent is guaranteed for Vitry on test? It would appear that the author's optimism is not shared by the Lopulco Company, because one would naturally think that if it were possible to get that efficiency on regular service, the test figure would be, if anything, higher. Mechanical-stoker engineers will guarantee 84 per cent under penalty. Such efficiencies could not, however, be obtained if the author's figures of the percentage of unburnt carbon in the ash from mechanical stokers were correct. He says that this is about 35 per cent, but in a well-operated station it should not exceed 10 per cent. It is possible that the author's views in regard to the efficiency of mechanical stokers have been formed without knowledge of the great improvements that have been made in them recently. For instance, he says that air-heating is not a common thing. Air-heating is, however, very important if high efficiency is required, and during the past two or three years my firm has supplied air heaters for a great number of boilers both in this country and abroad. Air-heating is a recognized method of improving the efficiency of mechanical stokers. The next point is in regard to flexibility, in the sense of the power to deal with a wide range of coal, and I differ from the author when he claims that fuel which is pulverized before being burnt gives the greatest flexibility. To burn pulverized coal there must be a certain minimum content of volatile matter in order to get free ignition and to maintain combustion. When I was in the United States last year, I was told that in several cases where pulverized coal was being burnt it had to be mixed with bituminous coal owing to the want of sufficient volatile matter in the fuel, and also in some cases auxiliary means of maintaining combustion had to be applied. That is, of course, very inconvenient. It is stated in the paper that the ideal fuel for pulverizing is one having 30 to 40 per cent volatile matter, although it is mentioned later that it can be burnt down to 5 per cent. There need be no such limitation with mechanical stokers, where any range of fuel having any volatile content or any amount of ash can be burnt. At the Birmingham municipal station I believe that 800 tons of coal are burnt daily, the coal having a heat value of between 8 000 and 9 000 B.Th.U.'s and 24 per cent volatile matter. The stokers burning that coal were tested a short time ago to ascertain how they would burn coke breeze having only 5 per cent volatile matter, and it was found that this could be burnt equally well with no alteration except as regards adjustment and regulation of the feed. We recently burnt some "unscreened metallurgical coke" which had a calorific value of 8 470 B.Th.U.'s and 1·75 per cent volatile matter. It was burnt on a stoker on which we burn Bothwell singles having a heating value of 12 000 B.Th.U.'s and about 25 per cent volatile matter. The author mentions low-grade fuel, but I do not call fuel of 12 000 B.Th.U.'s such as that he refers to at Milwaukee a low-grade fuel. I apply that term to fuel having less than 9 000 B.Th.U.'s, and there is no information in the paper as to how pulverizing would affect such a fuel. Another point is that, as shown by Mr. Harvey in his Report to the Fuel Research Board, the cost of pulverizing increases very much more rapidly than the percentage of ash, and to burn coal with a large amount of ash will add considerably to the running cost for pulverizing. The Lopulco plant appears to consist of a feeder and mixer, a new drier (which apparently has not yet been thoroughly tried), and the water screen, about the last-named of which the author is very enthusiastic. My firm has made two of these water screens, but only on the distinct understanding that we took no responsibility whatever for them. The author criticizes the steel-tube economizer and alleges that it will not last, but I put it to him that it will outlast the water screen. Referring to the remote control at the Ford plant, where one operator controls four boilers, or is shortly going to do so, by merely manipulating switches, there seem to be great differences in American practice, because according to Table 9, which deals with the Lakeside station where the author says there are six boilers at work, 63 men, excluding those in the pulverizing house, are employed. It certainly is not necessary to employ 10 men per boiler with mechanical stokers.

Mr. J. Train: The question of burning pulverized coal seems to be one of furnace design, and from the results presented in the paper the Lopulco system seems to have overcome the difficulty in connection with brickwork, etc. My firm tried pulverized fuel on a boiler some time ago, but unfortunately this boiler was designed for use with mechanical stokers with the result that the brickwork lasted about three days. It is therefore imperative that a combustion chamber designed for pulverized fuel only should be installed. I think that one of the main reasons why this method of burning fuel has not been adopted extensively in this country, is that only half measures have been taken when it has been tried. To be a success, it would seem that full measures are required

to obtain satisfactory results. It seems at present that the best results are obtained when the coal is burnt at the rate of 1 to 1½ lb. per cubic ft. of combustion surface per hour. As the author has mentioned the Ford plant, I should like to mention that my firm is at present installing two boilers each of 8 215 sq. ft. heating surface to be fired with a combination of pulverized fuel and blast-furnace gas. I would mention, however, that the pulverized system being installed is the unit system. I note that one of the principal claims for powdered fuel is the fact that varying grades of fuel can be burnt without difficulty. Opinions on this matter seem to have altered, as it was lately held that only fuel of good quality was suitable. As it is admitted that the system described in the paper is only economical when used with large central power stations, I would suggest that as these are usually some distance from the collieries it is advisable to use fairly good fuel on account of freight charges, etc. The best place for the pulverized-fuel plant would appear to be at the colliery, where there is a large surplus of fuel which is difficult to sell, and this fuel could be used by the colliery company under water-tube boilers to generate power for their own requirements. As the usual power station at a colliery is not large enough to justify the installation of the multiple system on account of capital cost, it would seem that the unit system is the more suitable. With this system, however, difficulties due to moisture arise, as if the free moisture of the fuel exceeds 4 to 5 per cent, choking of the discharge pipes takes place, and if the moisture content increases beyond that stated, the power required increases out of all proportion. I would suggest that to overcome this difficulty it would be a good proposition to add a vertical drier, such as that described by the author, to the unit pulverizer. With this addition I think that it would be possible to burn fuel for which there is no ready market, and which is available at collieries. In connection with the efficiency given by the author in Table 2, I think that it is in the smaller power stations, which cannot afford the capital outlay necessary with the multiple system, that the lowest efficiency occurs. As it is stated that the water screen is one of the principal reasons for overcoming the difficulties in connection with pulverized fuel, it is a question of using pure or distilled water. It is only at the largest stations that water of this kind is available, as in many stations it is not economical to put in evaporators for this purpose, owing to the large amount of make-up required. It would seem, therefore, that if water screens are barred on account of the quality of the feed water, we should concentrate on designing a furnace which does not require water screens, and this I think will be done as experience is gained in actual velocities in the combustion chamber and with air-cooled and hollow walls. The evaporations given in the paper for various plants are obviously not in connection with stoker plant, and here again pure water is essential to prevent trouble. It is regrettable that no mention is made of the actual work done by the water screen itself, or if this heating surface is included in the boiler heating surface when data are given regarding evaporation per sq. ft. If the actual performance of the water screen could be stated separately, it would give a much better idea as to the performance of the boiler itself and a better basis for comparison with stoker-fired boilers. I would suggest that this water screen has a greater effect on the performance than appears to be the case at first sight. For instance, it is stated in the paper that the water screen for the new boilers for Milwaukee has 320 sq. ft. heating surface per boiler. As this screen is subject to a very high temperature it is generally admitted that the evaporation at normal load will be in the nature of 41 lb. from and at 212° F. per sq. ft. of heating surface. This amounts to 13 120 lb. per hour. Taking, say, a boiler suitable for 50 000 lb. normal evaporation per hour, the water screen is responsible for approximately 24 per cent of this evaporation. If this figure is applied to the guaranteed evaporation per sq. ft. of boiler heating surface it reduces this figure considerably and gives a much better idea of the actual performance of the boiler. I should be glad if the author would give more information regarding the high evaporation and the amount contributed thereto by the water screen. The data for the repair bill for the pulverizer are unfortunately given for a case where good-quality fuel is being continuously used. It would be interesting to have the figures for the repair bill where the percentage of ash in the coal varies, and also the effect of various grades of coal on this item.

Mr. W. Ross: The paper will, I am sure, act as a basis for comparisons in costs and working efficiencies for some years to come. One is inclined to ask whether the boiler designer has no share in the increased efficiency obtained by the use of pulverized coal. Table 7 gives the highest evaporation per sq. ft. as 8·6 lb., the efficiency as 85·6 per cent, and the temperature of the stack gases as 272° F. These figures compare with the guarantees given for the new boiler plant at the Central Electric Supply Co.'s station, London. Of course the figure of 85 per cent efficiency for the London boilers is the test figure, but if banking losses are excluded is there any reason for supposing that the powdered-fuel boiler will keep cleaner than the other? I have mentioned the London station, but I think that when the several large boiler plants which have been laid down during the past few years are in full working order they should show efficiencies close to the 80 per cent mark, and that without putting in excessive heat-recovery surface, either in the economizer or air-heater. The figure of 77 per cent given in the paper for Dalmarnock is the average for the year with a load factor of 32 per cent, and the average stack temperature is 400° F. The coal used for banking at this station is about 5 per cent of the total, and if air-heaters or larger economizers were put in to reduce the stack temperature to, say, 250° F., then by eliminating the banking losses the efficiency would be about 87 per cent. It is, of course, admitted that with pulverized fuel the air supply is under better control, but I think that the big feature is the reduction of banking losses. My point is that the performance of an up-to-date stoker plant, combined with a heat-recovery surface sufficient to reduce the stack tempera-

ture to about 250° F., will compare favourably with that of a pulverized-fuel plant at 100 per cent load factor and a much smaller capital cost. Boiler plants do not run at 100 per cent load factor, however, so that some means would have to be adopted to overcome this handicap. I have had some experiments carried out on a 30 000-lb. C.T.M. type Babcock and Wilcox boiler with an oil burner fitted across the arch close to the fire door. The oil flame, which is only in service for about 15 minutes, takes the place of the arch until the coal is ignited and the arch hot. By this means it was possible to get a boiler on full load from cold in 30 minutes. This method appears to me to be worthy of further investigation, as although it might not be good practice to raise steam so quickly from cold, it might take the place of the banking of boilers over light-load periods. On page 417 the author gives the analysis of the ideal coal for pulverizing, and it will be noted that the ash should be less than 10 per cent. Now good washed singles and pearls supplied to Dalmarnock generally have about 14 per cent ash, and advocates of this system, when pulverized fuel is being discussed, usually make a great point of the fact that almost any sort of coal can be usefully and cheaply utilized. I should be glad if the author would say what would be the limit of ash percentage suitable for pulverizing in comparison with stoker gear. On page 411 he gives a summary of the auxiliary power required to operate a pulverized-fuel plant, and it is rather surprising to find that the fan power is given as 3 kW per ton of coal. On page 394 it is stated that 10 per cent of the air necessary for combustion is supplied at the burner at a pressure of 12 in. water gauge. To do this alone would take 22 kW, to say nothing of the separating fan at the pulverizers, and if the figures given on page 411, with the above corrections, are applied to the test given on page 401 under induced draught, then the electric feed pump in the one case and the conveyers in the other will be common to both, and the figures would be, for 8·3 tons per hour :—

	Dalmarnock	Pulverizing plant
	kW	kW
Induced-draught fan	68·3	—
Stoker drive	8·3	—
Electric feed pump	75·0	75·0
Conveyers	8·3	8·3
Pulverizing mills	—	99·6
Vertical driers	—	22·4
Pulverized-coal feed	—	6·65
Fans	—	22·00
Total	159·9	233·95

It will also be noted that the pulverizing plant does not allow for drawing the remaining 90 per cent of combustion air into the combustion chamber and passing it up the stack. In regard to the author's point that as the American engineers have done a great deal of experimenting and proved the system to be a success, it only remains now for the British engineer to start putting down plant and depend on the results obtained in America, I would remind him that quite a short time ago the multiple-retort stoker was quite the fashion in America and very fine results were obtained from it, but I have still to hear that the same type of stoker has been a great success in this country.

Mr. J. Bruce: It is claimed as one of the advantages of pulverized-fuel firing that the combustible in the ash can be kept to a value in the neighbourhood of 0·40 to 0·74 per cent of the total coal consumed. These figures can also be obtained on a competently operated mechanical-stoker unit. It will be noted on page 401, in the report of the tests carried out on boilers Nos. 9 and 10 at Dalmarnock, that under balanced-draught conditions the combustible in the ash is negligible. Actually it was below 0·5 per cent. On another test carried out a week ago on a single boiler unit at the same power station, this item in the heat balance was 0·53 per cent, the average rate of combustion being approximately 31 lb. per sq. ft. of grate area per hour, equal to a heat-liberation rate of 320 000 B.Th.U.'s per sq. ft. of grate area per hour. The furnace efficiency in this instance was slightly over 99 per cent. I am aware that values of this order are an exception in the case of the average mechanical stoker plant, but they show what can be obtained with the assistance of modern scientific instruments and an intelligent operating crew in the boiler room. Undoubtedly, as the author points out, the rate of combustion with pulverized fuel lends itself to very flexible control, and that with comparatively little difference in efficiency. While the control of combustion rates with pulverized fuel is more flexible, it is surprising the little effect that changes of load or the quality of the coal will have on the overall efficiency of a mechanical-stoker unit if competently and intelligently handled. On tests of large water-tube boiler units I have found it possible to obtain an overall efficiency in the neighbourhood of 80 per cent at all loads from $\frac{3}{4}$ full load up to, in certain cases, 40 per cent overload. These again are exceptions to general mechanical-stoker practice, and the credit is due not so much to the equipment as to the intelligence and adaptability of the boiler-room operating staff. One of the early objections to the use of pulverized fuel was the rapid deterioration of the furnace and combustion chamber refractories. A similar difficulty is occasionally experienced with mechanical-stoker plant when operating at high rates of combustion under balanced-draught conditions. I understand that refractory troubles at Milwaukee have been successfully overcome without any sacrifice of efficiency, and it would be of material benefit if the author in his reply would say how this was accomplished, and describe the nature or type of the firebrick used. Very great improvements have within recent years been effected in the design of mechanical-stoker plant, but the benefits derived from these improvements can only be realized if the plant is intelligently operated. Again, there are cases where stoker plant has been installed and unjustly condemned, due to the fact that in the first place no attempt was made to determine the correct combinations of grate area, arch length, and combustion-

chamber volume. In one case that I know of, the furnace efficiency of a mechanical-stoker plant was improved by from 6 to 7 per cent by re-designing the ignition arches. There is still room for improvement in mechanical-stoker design, especially in the direction of simple and accurate methods of scientific control. In my opinion, instruments for the measurement of coal, air, and flue-gas constituents should be looked upon as a part of the stoker equipment, and it is here that room for considerable improvement exists. More co-operation is required between the stoker manufacturer and the instrument maker, and there is a great field for valuable research work in this direction. Generally speaking, the author puts forward a very good case for pulverized fuel, but while such a system may be considered and adopted in the case of large new plants, I do not think that the benefits to be derived would warrant the scrapping of the mechanical-stoker plants at present in operation. A modern mechanical-stoker installation using preheated air and handled by an efficient operating staff should produce results not very far short of those obtained on pulverized fuel, and, taking into consideration the difference in capital cost, I think that pulverized fuel will find the mechanical stoker a strong rival for some time to come. The adoption of preheated air, the elimination of banking losses, and a general all-round increase in the efficiency of the majority of operating staffs, would go a long way towards bringing the efficiency of mechanical-stoker plants nearer to the average efficiency obtained with pulverized fuel. It is pointed out in the paper that quite a number of large power stations at present being erected are installing mechanical-stoker units. Is the author aware of the reasons that finally decided this course? The greatest factor influencing the economical combustion of coal and the generation of steam is the human element, and what is needed, equally as urgently as new and improved plant, is the education and all-round increase in status of boiler-room operatives. Taking the mechanical-stoker plants in operation to-day, I think that not 90 per cent of them are as efficiently operated as they could be. The same result would occur if pulverized fuel were adopted. Possibly 5 or 10 per cent of the plants would be operated in an efficient manner, the remainder falling into the class at present occupied by the majority of mechanical-stoker plants, and not until we reduce the effect of the human factor shall we be in a position to utilize efficiently new methods of burning coal. From the point of view of the chemist also, pulverized fuel does not offer the solution to the problem, inasmuch as it still entails the total consumption of the coal in the raw state, there being no provision for the extraction and recovery of the valuable by-products. The objection to the chemists' schemes of low-temperature carbonization, gas-fired boilers, and by-product recovery, is the enormous ground space required for the gas-producer plant. For instance, in the case of Dalmarnock something like 250 gas producers, with their accompanying auxiliary plant, would be required to supply steam for the present capacity of the station. It is my opinion, however, that cheap steam, the abatement of smoke, a cleaner atmosphere, and healthier industrial communities will only be obtained by a compromise between pulverized fuel and low-temperature carbonization, the boiler plants being fired by a combination of gas, and the pulverized coke from the producer plant, the coke not required by the generating stations being supplied for household consumption. A great amount of hard work must be done by our pioneers of science and engineering before the dawn of such an era, but steps should in the meantime be taken to make everyone in general, and engineers in particular, realize more fully that the black smoke polluting our industrial centres represents the prodigal squandering of civilization's greatest inheritance.

Mr. J. W. L. Jones: We ask ourselves why is it that so little progress has been made in what undoubtedly does represent a much better plant when dealing with a big installation, i.e. the use of powdered fuel. I think that it is perhaps to some extent due to the fact that manufacturers of powdered-fuel plant have been rather anxious to make a start in this country and are not sufficiently careful in the selection of the plant on which they are going to work, with the result that they have been putting installations into existing boilers where the setting is low and consequently the combustion chambers are too confined. Inevitably they have found themselves confronted with problems that are practically impossible to solve, with the result that purchasers have become disgusted with the experiments and progress has therefore been retarded. The paper states that the Americans have spent stupendous sums of money on the development of the powdered-fuel system, and this is undoubtedly true. My opinion is that powdered-fuel plants will not come into great vogue in this country except for large stations, where the large capital expenditure would be warranted. The paper does not give much information about the unit system, and I should be obliged if the author would say what is the difference in results attained by the two systems. With reference to Mr. McLaren's remarks as to what stoker practice had done, it is perfectly true that the development of stokers has gone on from year to year, and low-grade fuels, both anthracite and bituminous, present no great difficulties. Stokers have, however, definite limitations in certain directions. Stokers cannot burn efficiently low-grade fuels that are high in moisture content beyond 28 to 30 lb. per sq. ft. of grate, unless hot air is adopted, whereas with such powdered-fuel plants as are described in the paper there is practically no limit to the amount that can be burnt. It is merely a question of feeding into the furnace a sufficient quantity to obtain the capacity required.

Mr. R. B. Mitchell: It is rather remarkable that the Dalmarnock station makes a good basis of comparison with Lakeside so far as capacity is concerned; in fact, the two stations are very similar with respect to size and running conditions, the one exception being load factor, which at Lakeside is 60 per cent and at Dalmarnock 34 per cent. The author has made out a very strong case for pulverized fuel, and the figures which he puts forward are very striking. It is a most desirable thing to have a boiler-house efficiency of 86 per cent, and in the case of Dalmarnock an improvement

from 76 per cent to 86 per cent would mean a saving of £12 000 per annum. I think, however, that the hesitancy which the engineers in this country have shown in adopting pulverized fuel is due to the fact that they recognize that pulverized fuel is passing through a transition stage. In the development of everything new there is a stage in which changes are very rapid, and what is up-to-date to-day may be obsolete in a few months' time, and I think, therefore, that it is quite right that conservatism should be shown in this way. For instance, it is not yet certain whether a form of pulverized-fuel plant such as that put forward by the author is the right thing. I know that experiments are being carried forward in America with a design of furnace which is much smaller in proportion than that described in the paper; and the velocity of the furnace gases is very much lower. That form of furnace might be followed up with interest and compared in time with that described by the author. The problem of the emission of ash from the chimney is certainly one that would require serious consideration, especially in a station situated—as Dalmarnock is—in the midst of a closely populated district. Where a station is situated in the outskirts of a town there may be no difficulty, but a town station is different. The reference in the paper to low-temperature carbonization in conjunction with pulverized fuel is very interesting. I did not realize that such a thing was possible, and it is well to know that the residual from low-temperature carbonization can be burned in pulverized form with high efficiency. I agree with the author that it is vital that the utmost should be made of the fuel resources of the country.

[The author's reply to this discussion will be found on page 460.]

North-Western Centre, at Manchester, 18 December, 1923.

Mr. A. B. Mallinson: Within the last month I have been through some of the typical pulverized-fuel stations in the United States, where pulverized fuel has made enormous strides during the last two years. I must admit that what I saw at Cahokia and at the River Rouge plant of the Ford Company was wonderful. Take the Union Electric station at Cahokia, St. Louis. Quite apart from the question of pulverized fuel, that station impressed me as being a wonderful monument to American "push." A station with two 30 000-kW turbo-generators in it had been virgin ground in June 1922; the first pile on the bank of the Mississippi was driven in that month; when I visited the station on the 18th November, 1923, they had been generating for over a month, and the whole of the concrete sub-foundation work and condenser pit had been put in for another two 40 000-kW sets. They told me that for many months they had had 2 200 contractors' men working on that station, and the day I was there there were 1 600. There are 8 Babcock boilers each of 17 800 sq. ft. heating surface. It is almost uncanny to see the simplicity of operation at that station. What is called the Quigley system is used for moving the pulverized fuel from the pulverizers to the bins. It is dropped from the pulverizer into a vessel which holds, I think, 6 000 lb. of coal, and then the operator "shoots" it by compressed air first to one boiler bunker and then to another. There has been a lot of talk about the danger from explosion. Incidentally I should like to know whether the author has heard of the very onerous conditions which the National Fire Protection Association Committee a short time ago drafted at their annual meeting in Chicago. At Cahokia the pulverizing plant backs on to the boilers, and they have taken care to put a strong reinforced concrete wall right up from top to bottom, and the other side is all glass windows, the reason being that if there is an explosion they want it to go outwards. I was told that so far they have not experienced any trouble with the plant. After that I saw the plant of the Ford Motor Co. at the River Rouge, Detroit. That plant was different from the Cahokia station in that the station had been some time in operation and was in a practically finished condition. The author is quite right in what he has said about the number of the staff. What he did not mention is that everybody in the boiler house at the station is dressed in a white duck suit, and there is no sign whatever of coal dust or ash on the floors, or the tops of pipes, or anywhere. When I saw it the station was using just under 70 per cent of blast-furnace gas, and the remainder was pulverized fuel. The pulverizing plant is in a separate building, and the pulverized fuel is brought up by screw conveyers to the hoppers or bunkers over the tops of the boilers. The author gives figures in regard to the size of these stations. The remarkable thing is that they do not look big, owing to everything being symmetrically proportioned. The chimneys at Cahokia and River Rouge are all over 300 ft., but they looked no higher than an English power station chimney. I think that the author has rather run down the Englishman and, in making comparisons between modern British practice and modern American practice, has taken as his basis data which he has collected in this country during the past 10 or 15 years from plants many of which we know cannot be regarded as typical of plants which rely for their existence upon the generation of electricity for profit. In many cases they are simply part and parcel of a big works equipment. With regard to the question of ash, the Ford station is reasonably clean outside, but in the paper it is admitted that $17\frac{1}{2}$ per cent of the ash goes out of the top of the chimney. I wonder what a Manchester smoke nuisance inspector would say about that. The high chimneys must undoubtedly carry the dust some distance before it is deposited; that is well known in the paper trade. I cannot quite understand Table 8. I was told in the States that no carbon was left in the ash from these plants—at any rate it was under 1 per cent; but in the heat balance we get 0·5 per cent in the first instance and 0·9 per cent in the last. Further up that table under "Ash and refuse" we see figures of 3·6, 6·26 and 0·45 per cent, which added together total 10·31 per cent of carbon in the

ash. Is that burned effectively, or has it to be handled over and over again before it goes back to the boiler? The automatic control at the Ford works is certainly wonderful, but I do not think that it could be adopted anywhere else. The chief engineer of the Lopulco Company said that the Company are not keen on the automatic system. Incidentally, I heard that the Bailey meter was giving wonderfully good results with the automatic control. At Cahokia 4 of the 8 boilers were to be automatically controlled. On the question of maintenance, both at the Ford works and at other works where other systems were in use the maintenance of the pulverizers is not a big matter. In Mexico with similar pulverizers for pulverizing rock, I find that the maintenance question is not a big matter if the plant is correctly installed. I saw another system working at Chrome, New Jersey, where one could hardly see the pulverizer for dust. The plant, which was quite small, had been running 3 years like that and they had never attempted to clean the pulverizer. Handling 200–300 lb. of Pennsylvania bituminous coal per hour, a set of paddles lasts here for 1 600–1 700 tons, or about 1 400 working days.

(*Communicated*): From the paper one would consider that the development in the United States is practically entirely confined to the somewhat complex Lopulco system. The self-contained unit systems, however, are being developed in the States and elsewhere just as rapidly. Unit systems are extremely simple in comparison, and must effect a very material saving in capital outlay—both in plant and buildings. A properly designed unit pulverizer will not only pulverize the fuel but will also introduce continuously and uniformly the desired mixture of air and powdered fuel into the furnace. The impression which I formed in the States was that for plants under, say, 10 000 kW no case at all could be made out for the Lopulco system. The following data are for two typical cases where the "Aero" unit system is used.

Kansas City Southern Railway.—This plant comprises a battery of Heine boilers, each rated at 350 h.p. One boiler was at first fitted and, after experience of operation, four other sets have been put in.

PITTSBURG POWER PLANT WITH PULVERIZED FUEL, SEPTEMBER 6, 1922.

Test run (8 a.m. to 4 p.m.)	8 hours
Total coal burned	19 443 lb.
Total water evaporated (actual weight)	157 932 lb.
Average boiler pressure	114·6 lb. (gauge)
Average steam temperature	340° F.
(NOTE.—Superheater was blanked off during test, and while this temperature shows slight superheat it was disregarded in this test—only dry heat assumed.)	
Average feed-water temperature	168·5° F.
Average room temperature	92° F.
Average amperes at pulverizer motor	128
(NOTE.—Motor is a 50-h.p. 50° motor, and at the above load is only 57 % loaded.)	
Average voltage of circuit	220

Analysis of coal burned (on basis of coal as fired):—	
Moisture	1·28 %
Volatile	31·36 %
Fixed carbon	44·54 %
Ash	22·82 %
Sulphur (in volatile percentage)	5·27 %
B.Th.U.	10 953
Factor of evaporation	1·087
Lb. water from and at 212° F.	171 672
Average rating of boiler	177·5 %
Combined efficiency	78·4 %
Lb. water per lb. of coal (from and at 212° F.)	8·8 lb.
Average h.p. (elec.) of pulverizer motor	38
(On basis of 20 lb. steam per horse-power and allowing 5 % line loss, 95 % generator efficiency and 95 % mechanical efficiency.)	
Per cent steam used as generated by boiler at 177·5 % rating	4·1 %
Average CO_2	14·5 %
(No oxygen or CO readings were obtainable on this test.)	
Average fall of draught through boiler	0·15 in. water

The Wheeling Steel Corporation.—The units here are fitted to Connelly boilers. The tests were not special in any way, and the comparison with the stoker-fired adjoining boilers agrees closely with the comparisons made with Dalmarnock and Milwaukee by the author.

Mr. S. L. Pearce: This subject has always had a fascination for me. When I visited the States in 1920, things were just beginning to move; at any rate I had an opportunity of seeing the original plant put in at Oneida-street by Mr. Anderson. Milwaukee—Lakeside—had not started up at that time; it started up a couple of months later. I also had conversations with the chief engineers of the various stations which have been referred to this evening. What seems to me most remarkable is the complete change of opinion which apparently has come about in the States in the matter of pulverized fuel. In 1920 there was hardly an engineer other than Mr. Anderson who had a good word to say for it. To-day the facts speak for themselves. Whatever we may think about the question, several prominent engineers in the States are convinced that there is sufficient in it to warrant them putting down plants. When I came back from America one of the first things I did was to obtain estimates for the application of what are known as the "central" system and the "unit" system to existing plants in Manchester. I was prepared to admit, for the purpose of calculation, that a possible saving of 5 per cent in efficiency was obtainable. But even on that basis, and on the capital estimates submitted, I could make out no case whatever for the application of pulverized fuel to existing plants. Of course at that date the central system, at any rate, was extremely complicated; it involved the installation of a great deal of plant which is now eliminated, and the capital cost was necessarily high. I am prepared to admit that there has been a material improvement in

designs, but I still think that it is very difficult to make out a case for applying a pulverized-fuel installation to existing boiler plant; I am inclined to think that in the majority of cases the capital costs will still outweigh the savings. Therefore I feel that it is essential that the question of pulverized fuel versus mechanical stokers should be tried out if possible on a new job. Without attempting to throw any discredit or doubt upon the figures which have been sent over to this country from America, I should like to see the question settled in a British boiler house with boilers working under identical conditions. I am inclined to agree with the author that the utmost gain we can expect to get from the adoption of pulverized fuel, as compared with the present mechanical appliances, is 5 per cent. I think that is an absolutely outside figure. I see that the Milwaukee results are given as 85–86 per cent. These, I take it, are not the efficiencies for the individual units but the efficiencies for the boiler house as a whole. I think I read in the last publication of the Prime Movers Committee of the National Electric Light Association, U.S.A., that Mr. Anderson claimed that during the last 12 months he

TESTS ON POWDERED COAL AND STOKER-FIRED CONNELLY BOILER AT THE CREEK PLANT OF WHITTAKER-GLESSNER CO.

	Powdered coal	Stoker fired
Date of test	22nd Aug.	23rd Aug.
Fuel-burning equipment	Aero Pulverizer	Underfed Stoker
Heat balance:		
Loss due to moisture in coal	0·22 %	0·24 %
Loss due to burning of hydrogen	4·13 %	4·40 %
Loss due to moisture in air	0·25 %	0·28 %
Loss due to heat in dry flue gases	9·30 %	13·20 %
Loss due to carbon in ash	0·00 %	4·22 %
Loss due to radiation (assumed)	5·00 %	5·00 %
Total loss in heat	18·90 %	27·34 %
Efficiency of boiler and stoker	81·10 %	72·66 %

The heat balance was calculated on the basis of coal analysis as submitted by the Pittsburg Testing Laboratory, viz.:—

		Powdered coal	Stoker fired
Ultimate analysis of coal by weight	Hydrogen	4·74 %	4·72 %
	Carbon	68·08 %	67·84 %
	Nitrogen	1·33 %	1·26 %
	Oxygen	7·07 %	7·19 %
	Sulphur	4·87 %	4·84 %
	Ash	13·91 %	14·15 %
B.Th.U. per lb. dry coal		12 647	12 623
Analysis of ashes:			
	Carbon in ashes	—	29·83 %
	Ash	—	68·22 %
B.Th.U. per lb. dry ashes		—	4 699

The average of the principal results obtained during the test is as follows:—

	Powdered coal	Stoker fired
Total water evaporated, lb. for 24 hours	1 108 756	1 205 000
Total coal used, lb. for 24 hours	105 352	125 567
Equivalent evaporation from and at 212° F. per lb. coal, lb.	11·2	10·2
Boiler efficiency corresponding to above	86·1 %	78·3 %
Average rating developed during test period of 24 hours	172 %	186 %
Flue gas analysis, by volume: CO_2	14·4 %	13·7 %
O_2	4·0 %	4·4 %
N_2	81·6 %	81·9 %
Temperature of feed water	208° F.	212° F.
Temperature of flue gas leaving boiler	470° F.	649° F.
Room temperature	77° F.	85° F.
Average steam pressure (gauge)	190 lb.	190 lb.
Average superheat	27 deg. F.	20 deg. F.
Moisture in coal	2·08 %	2·25 %

It will be noted that there is a difference in the figures of efficiency as calculated from water credited as evaporation and as given in the heat balance. These figures are:—

	Powdered coal	Stoker fired
Efficiency from water measure	86·1 %	78·30 %
Efficiency in heat balance	81·1 %	72·56 %
Efficiency difference	5·0 %	5·74 %

had been able to improve the Milwaukee figure from 85 per cent to 88 per cent. I am not quite clear to what he refers. If it means a general boiler-house efficiency of 88 per cent it is truly an astonishing figure. If, on the other hand, it refers to individual boiler units, we might expect that the general boiler-house efficiency would be as high as 85 or 86 per cent. I want to compare that with the results which we are getting at Barton to-day. We have had given to us in the paper the figure from Dalmarnock, which is taken as a typical modern station. It is 76·5 per cent, with a 34 per cent load factor. I should say, first, that the guarantee we have got from the boiler manufacturers for individual units at Barton is 85 per cent on full load. Whether we shall get that figure or not I am not at present in a position to say. What I can say is this, that the average boiler-house efficiencies, week in, week out, vary from 81 to 82 per cent. That means there is an improvement of at least 5 per cent over Glasgow. I understood the author to say that the figure for Connors Creek was 75 per cent, and that there was an American station which showed 81 per cent; perhaps it was Delaware. The point I want to make is that the Barton results of 81–82 per cent (and we have had a week with 82·5 per cent, and I think that even that figure is capable of improvement) apparently set up a new standard, at any rate for British boiler-house practice. These results have been obtained with coal of a calorific value of 11 000 B.Th.U.'s and a 45 per cent load factor. In passing, I should like to refer to the Vitry (Paris) figures. They seem to be remarkable. How much of it is due to pulverized fuel I cannot say. The boilers are easily the largest in Europe, judged from the evaporation point of view. On the other hand, the heating surface of the Vitry boilers including economizers is about 1 400 sq. ft. less than that of the Barton boilers. Their evaporation is 140 580 lb. with 12 000 B.Th.U. coal, against the Barton figure of 100 000 lb. with 10 000 B.Th.U. coal. Even making the correction for the higher calorific value, the greater output of the Vitry boilers compared with Barton will be seen. This problem of pulverized fuel is divisible into two parts, the question of preparation machinery and the question of combustion. I am inclined to agree with the author that we need not trouble ourselves very much about the preparation of the plant: I think that problem is solved; but in regard to the question of combustion, success can only be obtained by correct design of the furnace. In that respect one is very interested to hear what the author has had to say about the necessity for adopting the circulating-water screen and the hollow side-walls and bottoms of the furnaces. In connection with a proposal which I made to the boiler makers at one of our stations in Manchester, I put forward this circulating-water screen arrangement, and asked for their opinion. They were decidedly opposed to it, and went so far as to suggest that they did not think a boiler insurance company would insure a boiler with that attachment. When it was pointed out to them that the design was identical with one of those in successful operation in the States, as shown on the screen to-night, it made no difference to their view. This subject is of far too great importance to power station engineers to admit of any unfair or too critical attitude. Savings in power station costs are mainly to be made in the boiler house. I think everybody will agree with that. Therefore we have got to keep an open mind on this question, and I appeal to the boiler and stoker manufacturers, and to all interested, to approach these questions in a proper and progressive spirit. If a case can be made out for pulverized fuel in this country, whichever method is adopted, either the central or the unit system, I hope that no hostile interest will be allowed to stand in the way of its adoption. I have seen some very bad examples of what can take place through slagging resulting from incorrect design of ash chambers; and I emphasize this, that the combustion end of the problem is the serious one that wants tackling.

Mr. W. Eccles: On pages 402 and 403 it is stated that under most modern conditions pulverized fuel is working at 86 per cent efficiency and mechanical stoking at 81½ per cent efficiency; and that the resultant saving of 5¼ per cent in the coal bill is due to pulverized fuel. This may or may not be correct, but the figures given for Lakeside and Dalmarnock most certainly do not uphold the statement. According to the table given on page 403 the maximum efficiency of Lakeside is at about 170 per cent rating. At full load the average efficiency is 88·5 per cent, and it drops to about 86 per cent at the long overload rating. The only corresponding figures for Dalmarnock are those given on page 401, and of these only the balanced-draught test is a fair but very unsatisfactory comparison. I say "fair" because balanced draught is a standard method of operation, and "unsatisfactory" because a 3-hour boiler test cannot be a reliable one for efficiency. However, as the author has left me no other choice, I must take the efficiency for mechanical stoking as 83·5 per cent. This shows the Lakeside plant to be from 2·5 to 5 per cent more efficient than the Dalmarnock plant, which approximately corresponds to the author's comparative statement of efficiency figures which I have just mentioned. I should like, however, to draw attention to the fact that this difference in efficiency has nothing at all to do with pulverized

	Lakeside	Dalmarnock	Efficiency in favour of Lakeside
(1) Combustible in ash	5 %	Negligible	0·55 %
(2) Per cent of CO_2	14·6 %	14·5 %	+ 0·05 %
(3) Extra power required	100 b.h.p.	—	— 0·8 %
(4) Coal required for drying *	1 %	—	— 1 %

* The coal required for drying might fairly be neglected as this drying is done by flue gases in the more recent plants.

fuel; in fact, on examining the test figures on pages 401 and 404 (Test No. 2) it will be seen that if Lakeside had been fitted with the Dalmarnock stokers and burning Dalmarnock coal a higher efficiency would have been obtained than was actually done with the pulverized fuel used. Let us first take the factors directly affected by the method of stoking, which are as stated in the table on page 443. These figures show that the method of stoking at Dalmarnock is more efficient than that at Lakeside. The reason that the overall boiler-plant efficiency shows Lakeside to be a better plant than Dalmarnock is clearly seen from the following factors, which are not affected by the method of stoking:—

	Lakeside	Dalmarnock	Efficiency in favour of Lakeside
(1) Chimney gas CO_2	11·9 % *	14·5 %	(Included in temperature correction)
(2) Chimney gas temperature	196° F.	414° F.	+ 4 %

* The drop in the amount of CO_2 at Lakeside from 14·6 to 11·9 per cent indicates a leakage of air into the boiler of approximately 0·30 per cent of the air required for combustion, a state of affairs which should be explained especially in view of the stress laid on the importance of keeping down the excess air to a minimum.

This temperature difference is partly accounted for by the air leakage and completely when the following comparative facts are noted for the same B.Th.U.'s transferred:—

	Lakeside	Dalmarnock
Feed water temp. ..	129° F.	158° F.
Boiler heating-surface ..	165 sq. ft.	100 sq. ft.
Economizer surface ..	125 sq. ft.	100 sq. ft.

Summarized, the facts are:—

	Per cent
Comparative loss at Lakeside due to pulverized-fuel firing	1·3
Comparative loss at Dalmarnock due to remainder of plant	4
Net gain of Lakeside over Dalmarnock..	2·7

This very closely approximates to the difference in efficiencies (87·1 %–83·56 %) when allowance is made for the extra power required by Lakeside.

Is there any need to explain further the reason why Lakeside is more efficient than Dalmarnock? The Lakeside boiler is obviously more expensive than the Dalmarnock boiler, and this brings me to the point that it is not thermal efficiency that matters, for that can usually be improved by buying more expensive plant; but the point is, what efficiency does it pay to buy? I have no doubt it paid Lakeside, on their 60 per cent load factor, to buy 87 per cent, nor do I doubt that on their 34 per cent load factor Dalmarnock were justified in buying 83·5 per cent. One small point which I noticed in going through these figures, is that the air leakage at Lakeside, between the furnace and the chimney, amounts to about 30 per cent. There does not seem much object in reducing the excess air to 22 per cent at the expense of brickwork troubles, etc., when it might as well have been 50 per cent if the leaks were stopped, without reducing the efficiency of the plant. I come now to the author's conclusions on page 416.

Efficiency.—I hope that his opinions here are based on something better than the figures which he has submitted; otherwise the case for pulverizing falls rather flat on the grounds of efficiency. Personally I feel that there is some extra efficiency to be gained by pulverizing, but the facts presented by the author do not prove it, although he claims 5¼ per cent on this account. In view of this miscalculation I do not see how we can possibly accept the statement that under ordinary conditions the saving would be 9 to 10 per cent and in most existing stations 15 to 20 per cent, and I think that we must agree that in this respect the author's case is not proven.

Unburnt fuel in the ash.—Again the Dalmarnock and Lakeside figures are contrary to the claims made, but it is possible that with a fusible ash the pulverized fuel might prove to cause the lesser loss.

Stand-by and banking losses.—This is a 2 to 5 per cent gain for pulverizing, but why? I cannot see any particular reason one way or the other, when all the dampers are closed. Can the author give us any comparative figures on this point? No doubt heat can be lost by careless banking, but we are comparing good practice in each case.

Ease of scientific control.—This apparently implies central control by a highly-skilled person who has long-distance CO_2 and temperature indicators besides him; and although a great deal more could be done in this direction with mechanical stokers than is done at present, it is possible that pulverized fuel lends itself more readily to this than do mechanical stokers.

Labour costs.—I do not understand how it can be that under similar conditions there is less labour involved in pulverized-fuel plant than in stoker plant. Water, coal (apart from pulverizing), ash and fan services require the same attendance in each case, and surely a chain-grate stoker cannot require more attendance than a pulverizing mill and drier. Again it seems to be a case of capital expenditure versus labour.

Auxiliary power consumption.—Here again the feed water, coal- and ash-conveying and fan services are common to both systems and the power for pulverizing must be in excess of that required to drive stokers. Naturally, if the amount of power required is expressed as a percentage of the total boiler output, it is a very

small amount; but my point is that the pulverized-fuel plant requires more power than the stoker plant.

Maintenance costs.—I note and agree that it is usually very difficult to get such information for comparison, but in this respect I have in my possession complete detailed costs for each piece of apparatus in a station, including—general; brickwork; stoker; soot blower; piping and valves; forced-draught fan and ducts, etc.; economizer; induced-draught fans; coal bunkers; ash hoppers, etc., for the year 1922, of a similar large station in America using mechanical stoking; and whilst I feel that I am not at liberty to publish this information without referring to the manager concerned, I have no doubt that permission could be obtained if the author would produce similar detailed costs for a pulverized-fuel plant, such as Lakeside, which he refers to on page 396 as being "run on thoroughly modern and scientific lines both of control and costing."

Ash troubles.—I note that, according to the tests mentioned, Lakeside apparently discharges from 30 to 50 per cent of the total ash, and at Dalmarnock about 30 to 45 per cent of estimated ash seems to be unaccounted for.

Capital costs.—Here again I think that the author is very optimistic as regards pulverized fuel, but I think he need not have been so vague in the matter, for the bill for material, different in each case, could easily have been stated, from which it could have been seen how he arrived at his statements.

Mr. E. H. Hutchinson: The title of this paper is rather misleading; it should rather be a description of the Lopulco system, and it would have been interesting to hear something about other well-known systems of pulverized coal, such as that of the Powdered Fuel Co., Ltd., the Holbeck Engineering Co., Messrs. Alfred Herbert, Ltd., Messrs. Fraser & Chalmers, Ltd., and the Société Anonyme pour l'Utilisation des Combustibles of Paris, with whom are associated Simon-Carves Ltd. of Manchester. The plants installed by the last-named company have a capacity of $1\frac{1}{4}$ million tons of coal per annum. It is rather surprising that the author should lay so much stress upon American figures when this French Company already have over 100 pulverized-fuel plants at work in France, of which 60 are applied to boilers. I might mention the plant installed by them at the Citroën motor-car works in Paris. These works were fitted up with pulverized-fuel apparatus by this French Company, and during the war they were pulverizing lignite and peat, with which mixture they were firing the whole of their boilers and reheating furnaces dealing with billets up to 5 in. square. Another example is that of the Mines de Bruay in the North of France, where they have installed a central power station from which electric current is supplied to outlying districts extending as far as Calais, which is some 80 miles distant. Here there are two boiler houses, each having a battery of 16 boilers. Considerable trouble was experienced with the refuse coal that had to be burned and the Bruay Company experimented with every kind of mechanical stoker and chain grate and also designed stokers of their own, but in no case were the results satisfactory. Ultimately it was decided to experiment with pulverized fuel on one boiler only, by means of a unit machine. The results obtained from this one boiler were so satisfactory that one battery of 16 boilers was equipped with a central pulverizing plant. At this colliery there are two boiler houses - one equipped with mechanical grates and stokers and the other with the Simon-Carves system of pulverized-fuel firing and for the same quantity and quality of coal burned the boiler house fitted with pulverized fuel produces 50 per cent more evaporation, the coal burnt containing 25 per cent of ash. The results from this boiler house have been so efficient that the Bruay Company have recently placed an order with this French Company to equip 8 new large water-tube boilers at the same colliery, with another central pulverizing plant. Another installation just carried out by this French Company is a central pulverizing plant for the Cie des Mines d'Anzin, having a capacity of 42 tons per hour, and I think it will be agreed that this is by no means a small plant. I might mention also a central pulverizing plant installed at the Cie du Nord-Ouest Electrique (Centrale d'Abbeville), dealing with 12 tons of coal per hour. Why is it that we do not see a single Lopulco plant at work either in this country or in France? I think that Mr. Bell stated last week that with the extension of the pulverized-fuel plant recently installed a saving of about £5 000 had been effected at Hammersmith after working the boilers 9 months. That is a statement of fact and should be considered very carefully because, although the author talks of efficiencies, he has given no figures as to the actual savings effected in the plants mentioned by him. Another point that requires careful consideration is the water screen used with the Lopulco system to prevent the ash slagging. With the earlier pulverized-fuel plants considerable trouble was experienced owing to the fused ash having a deteriorating effect on the brickwork of the combustion chamber. The patent combustion chamber and ash pit used with the Simon-Carves system of pulverized fuel has obviated all difficulties. With this system about 40 per cent of the ash is fused, flows down the sides of the combustion chamber and is cooled whilst falling into the ash pit, and does not adhere to the brickwork of the combustion chamber in any way. The ash pit only requires clearing about once in 6 hours, and the slag taken out occupies about one-tenth the volume as compared with the clinker taken from chain-grate stokers; or, in other words, for every 10 trams of clinker from chain-grate stokers we get about 1 tram from pulverized fuel. The brickwork of the combustion chamber is a very important point, and the above French Company have experimented for some years in order to find a brick that would resist the fluxing action of the slag, and they now use such a brick which has a melting point in the neighbourhood of 3 350° to 3 400° F. I have seen combustion chambers which have been in continuous use for 18 months and are in almost as good a condition as when they were first started up. If, as the author says, in the Lopulco system the ash is brought down in dust, it would appear that the greater part of the ash in the coal cannot be fused. In a combustion chamber fired with pulverized fuel with a sufficiently high temperature, there is a fused ash deposit all over the combustion chamber, not only on the bottom but on the sides, and

it is difficult to understand why, if the ash is fused, the sides of the combustion chamber used in the Lopulco system should not have a deposit of fused ash on them. I think that the author gives the temperature in the combustion chamber of the Lopulco system as about 2 100° F. With the Simon-Carves system the temperature in the combustion chamber is about 2 700°–2 800° F. A temperature difference of 700 degrees F. must have a remarkable effect on the efficiency of the boiler. It has been proved by experience that the efficiency of the boiler itself is much higher with pulverized fuel, and this is shown by the fact that the degree of superheat is much lower and the temperature of the waste gases entering the economizer is about 90–100 degrees F. lower, as compared with a boiler fired by mechanical stokers or grates. In my opinion, boilers fired with chain-grate stokers leave much to be desired as regards efficiency, when we consider that in firing a boiler fitted with chain-grate stokers we have only a certain time in which the coal may be burned, and in order to burn the coal in the time available we require an induced-draught fan giving a suction of $1\frac{3}{4}$ in. to $2\frac{1}{2}$ in. With this high suction a large volume of air at a very high velocity is pulled through the fire (in fact, far too much air) with a consequent reduction in temperature and percentage of CO_2. I think that if we take many of the power stations in this country we shall find that the percentage of CO_2 in boilers fitted with chain-grate stokers over a month (not 8 hours or 24 hours) is somewhere in the neighbourhood of 7 to 8 per cent, and not 14 to 15 per cent as is obtained continuously with boilers fired with pulverized fuel. With the Simon-Carves system of pulverized fuel a suction of only $\cdot 1\frac{1}{2}$ in. to $\frac{3}{10}$ in. water gauge is required, and it is partly due to this low suction that so very little dust is emitted from the chimney. To any one conversant with the handling of air and gas and the collection of dust, the dust difficulty could easily be overcome, and it is quite possible to install a plant with a guarantee that not more than 5 per cent of the dust would be discharged from the chimney. The bulk of the dust produced with the Simon-Carves pulverized-fuel plant never reaches the chimney, but is caught in hoppers in the economizers and the main flues. As to the question of power absorbed by central pulverizing plants, this is considerably lower as compared with boilers fitted with chain-grate stokers and balanced draught. In one particular case dealing with a plant of four boilers each evaporating 50 000 lb. of water per hour, there was a saving in running costs of 80 h.p. per hour. The author does not refer to the unit type of pulverizer. Although more costly in power this type has certain advantages over the central plant, in that the fuel does not require drying. In a well-designed machine, coal containing 10 per cent of free moisture can be pulverized, and this has been done in this country. In one plant fitted with unit machines the saving of coal per boiler, compared with others fitted with chain-grate stokers, is 25 to 30 tons per week. The author states that the unit machine is not capable of fine regulation. This machine is, however, being applied very extensively to metallurgical furnaces, which require a much finer control than a boiler plant. We have reheating furnaces at work with pulverized fuel with an output of 40 tons per hour.

Mr. T. R. Wollaston: I am not a believer in firing boilers direct with coal, which I think we must now agree is more or less crude, nor yet with pulverized coal, which is, however, a step in the right direction; I hold that raw coal should be turned into the ideal fuel, viz. gas. The author and other speakers have suggested as good practice 50 per cent excess air and 12 per cent CO_2 when working with ordinary stokers; and it has been stated that with pulverized fuel one can work with 20 per cent excess air and something like 14 or 15 per cent CO_2. I know from long experience that with gas one can work with no excess air, and it can be done continuously with from $17\frac{1}{2}$ to 18 per cent CO_2 in chimney gas. Some few years ago —about 1917, I think—several papers were written touching upon boiler firing by recovery gas. We have heard to-night that all these remarkable results have been obtained with pulverized fuel within the last four or five years. Certainly the progress is wonderful, but there has also been considerable progress in connection with gas firing. I hope that I shall not appear to be arrogant in claiming to have proved, upon a sufficiently large scale, advances in producer-gas firing potentially as great as those accomplished with pulverized fuel. Five years ago one could regard the recovery gas producer as capable of working at less than 70 per cent thermal efficiency (cold gas) and the gas-fired boiler as at 82 per cent efficiency, an all-round thermal efficiency of under 60 per cent. To-day these figures might be 80 per cent (cold gas) efficiency for the producer and probably 92 per cent for the gas-fired boiler, an all-round efficiency of at least 73 per cent for the combination. These combined efficiencies are below those which the author has given us, but one would ask: Do we want high thermal efficiencies wholly for scientific reasons or mainly as a means towards generating electrical energy at the lowest possible cost? The general public is more concerned with cost. The author has mentioned some remarkable points in pulverized-fuel firing as regards, for instance, ease, certainty, and consistency of handling and burning, range and condition of raw material, facility for remote control, cleanliness, and so on. I say with conviction that gas firing possesses these features in a much greater degree. I believe that there are three all-important conditions in the choice of site for a power station:—(1) Cheap central location. (2) Abundant cold water supply. (3) Easy access for fuel. As water can be piped over long distances comparatively cheaply it may be regarded as being the least important. I would point out that gas can be piped even more cheaply, particularly if the mains be laid simultaneously, so that with gas firing, coal delivery, storage and handling may be centralized miles away from the boiler house. The latter may be as clean, light and open as the turbine house, and there will be no smoke, grit or ash handling. I have been much encouraged to-night in noting the boiler house sections including pulverizing and storage plant as shown on the author's slides. I roughly estimate that with gas-fired boilers every one of these boiler houses would be reduced in cross-sectional area (or cubic content)

by at least 50 per cent, and the capital cost in even greater proportion, due to reduced excavation and foundation work. In short I think that the total capital cost of a gas-fired boiler house with remote gas plant and gas mains would not greatly exceed that of the stations shown on the slides, and that the running costs, having in view the use of the cheapest fuels, would not be higher. So far I have not referred to by-product recovery, which may safely be regarded as showing a net rebate of 4s. per ton of coal. I am now engaged upon a careful analysis of the subject, the results of which I hope shortly to publish. My case is that, had the same skill and energy been given to producer-gas firing during the last 10 years as has been given to the utilization of pulverized fuel, the former would have shown results in every way more economical, hygienic and scientific.

Alderman W. Walker: I agree with Mr. Pearce that everything on this important subject of pulverized fuel should be received not with hostility but with an earnest desire to learn what has been done and what are the results. I had not read the paper very far, however, before a feeling of opposition was aroused, because it was borne in upon me that the paper did not deal with the burning of pulverized fuel as a principle or as a general system, but merely with one particular method. It would have been better if the author had obtained information as to what other people in the United States have been doing and what other plants have been installed, rather than confine himself to one type only. I think that if he had put before us the advantages of pulverized fuel in general, explained the principal systems, how and where they differed and what he considered to be the strong and weak points of each, so as to assist us to come to a decision on the matter, the paper would have been more valuable. He suggests the idea all through the paper that there is no other method than the particular one to which he has confined his remarks. We have to consider one point in connection with this system which will be likely to cause a lot of trouble to power stations in this country, namely, the question of the disposal of the ashes from the chimney. Taking the higher figure on one of the slides which the author has shown to-night, it would mean that 50 per cent of the ash would go up the chimney, and, taking the lower figure, it would be 25 per cent. Remembering the situation of a large number of the power stations, can we consider depositing anything approaching 25 or 30 per cent of the ash from the chimney without at once causing trouble with the local authorities, complaints from the residents of the district, and applications for injunctions to stop it? That is one of the points which will have to be faced in connection with the system. I notice that on page 385 the author refers to the unit system, which he says is not applicable to large plants. I should like to know something about that. I find on making inquiry that there are quite a number of other plants at work and that those who have them are quite satisfied. I do not think, therefore, that the other methods ought to be turned down as has been done by the author on page 385, because information could have been obtained from the users and makers of these, both in the United States and elsewhere, just as easily as from those who are putting forward the one system described. In addition to the single plant which he says is being installed in France, there are already 40 or 50 plants of other makers installed. I hope that the author will give us through the Institution or through some technical paper a description and figures which will enable us to judge what are the advantages and disadvantages of the various systems of burning pulverized fuel.

Mr. A. Stubbs (*communicated*): Facts of a divergent nature are placed side by side in the paper whilst the obvious inferences are far from being substantiated. The Lopulco system as described appears to be the outcome of a certain amount of "dog logic." "Dog logic" results in action being taken on the spur of the moment without reference to many of the surrounding factors. The system provides for what looks like an overgrown furnace with mechanical stoker removed, and this development has presented difficulties of wall temperatures and ash disposal. Air cooling for the walls and a water screen for the ashes readily provides the solution, but the plant has a very makeshift appearance. It is easy to imagine that a more general survey would have resulted in a different arrangement, e.g. it might be possible to arrange the boiler surface like the surface of a truncated cone or the walls of a blast furnace and, should it be necessary to have refractory material to give the high-temperature radiation in order to support combustion, this would be suitably placed. The feature to be brought out is that any such outlook must involve the boiler manufacture and the combustion engineers. Co-operation between these two parties is not particularly evidenced by the Lopulco system. Boiler construction is so far from being standardized to-day that it does seem possible that users may be able in the future to buy units of surface capable of being arranged in any manner to suit the particular problem, which would of course leave the initiative largely in the hands of the combustion engineers. The list of plants installing pulverized-fuel equipment, as published by the Combustion Engineering Co., makes it very obvious that there must be some advantage. I have looked for this in the paper, but much of the talk regarding efficiency is like that of the misinformed salesman, who will persist in putting forward electricity on the score of efficiency even in those instances where no case could be made. The really important features are lost sight of because of his anxiety to stress the question of efficiency. The facility of control is probably one of the most important features of a pulverized-fuel plant. It would be very desirable to be able to govern the prime-mover output by means of the fuel valve rather than by the steam valves. I would ask the author whether the Lopulco system provides for the fuel to be shut off in emergency and at the same time for water to be supplied to the furnace instead. The question of control is the more important the larger the plant. I understand that some months ago water sprays were being fitted over the underfeed stokers for use in emergency at Gennevilliers. Referring to the author's statement of advantages up to the year 1920 (page 389):—

(1) Efficiency figures mean very little, for we can obviously get anything we wish by paying for it, and indeed the figures for pulverized-fuel plant seem to be low compared with those now being mentioned in connection with plants in this country. I was recently concerned with tests on a number of 30 000-lb. boilers in which the efficiency was 85·3 per cent. Certain boiler plants with mechanical stokers and air-heaters on the North-East Coast are stated to be capable of running at 86 per cent, whilst when visiting the Gennevilliers station I was told that the Stirling boilers were operating at 88 per cent.

(2) It is now the usual practice to return the riddling for combustion in connection with mechanical stokers.

(3) The high temperature of the flame seems to be a disadvantage so far as the walls and the ash problem are concerned. I should like to ask the author whether it has been considered to take air from the cooling towers for combustion in order to keep the temperature down. Water injection was put forward with internal-combustion engines for similar reasons.

(4) The transport question is increased with the pulverizing plant, but the convenience within the boiler house is probably greater. The Lopulco system, however, still provides for massive bunkers which obstruct the light and increase the cost.

(5) Whilst there would seem to be considerable scope for pulverizing under this heading, it does, however, seem that different coal requires different treatment. Some inconvenience was experienced at Gennevilliers with the mechanical stokers when the Ruhr coal supplies were cut off and it became necessary to get coal from Scotland, Wales and elsewhere.

(6) and (7) are probably notable advantages to be obtained by using pulverized fuel.

(8) There appears to be some doubt as to ease of scientific control as shown in the remarks under heading (6) on page 390, although it is difficult to see why this should be.

Disadvantages up to 1920.

(1) Any of the figures here quoted for the cost of preparation when made as a charge against the efficiency of the pulverized-fuel plant would be sufficient to condemn it upon this score.

(3) The cooling of the furnace by inlet air as now put forward is obviously inefficient, as this heat should be derived from a low-temperature source and not from the highest temperature of the system. Such practice limits the possibilities in connection with preheating the air by the chimney gases or exhaust steam, etc. Every temperature-rise of 100 degrees F. on the chimney temperature means reducing the efficiency by 4 per cent.

(7) The lighting system as invented by Prof. Thornton for use in coal mines might be of interest to the advocates of pulverized fuel. This system provides for electric lighting from a fairly high-frequency supply (approximately 160 cycles) at a reasonably low voltage, and it is claimed that it is quite proof against any possibility of causing an explosion.

(8) It appears that any hope of being able to pulverize with a higher degree of moisture content in the coal must be discounted on account of the danger from spontaneous combustion.

(9) More will be heard of the ash problem when pulverized fuel is introduced into the large English cities. Recently one of the large London stations operating with mechanical stokers had an injunction issued against them by the people on the opposite side of the Thames, and necessary action had to be taken in order to prevent the ash passing through the chimneys.

On page 392 there seems to be a point worthy of some considerable notice, namely, that the Lakeside station was completed and put in operation within 12 months. Similar progress on the civil engineering work on this side of the Atlantic does not appear to be usual. With regard to the Dalmarnock figures, I should like to ask the author whether he is in a position to state that with the two types of stokers in operation at this station, there is 4 to 5 per cent difference in the efficiency of the plant.

[The author's reply to this discussion will be found on page 460.]

North-Eastern Centre, at Newcastle, 14 January, 1924.

Mr. J. W. Jackson: The supply undertaking with which I am associated agree in general with the remarks made by the author under the heading of "Boiler Plant Efficiency." We have been able since early in 1920 to make investigations for ourselves with a powdered-fuel plant on one 20 000-lb.-per-hour boiler burning a very low-grade fuel. This fuel is so difficult to handle that with some types of chain-grate stokers it is commercially impossible; but with a pulverized-fuel plant the burning of the fuel is quite easy. The boiler subjected to this treatment gives the maximum evaporation of any of the 12 boilers installed in the station, while its maintenance charges both in the furnace and mechanically are considerably lower than those of the ordinary chain-grate stoker. The efficiency and heat transference are at least as high under commercial operation as it is usual to obtain with a boiler of this type and size under chain-grate-stoker conditions on official tests where the manufacturers' representatives are required to secure the guaranteed efficiency. Although on many boiler trials efficiencies as high as 83 and 84 per cent have been claimed for boiler and economizer, we are at the same time quite satisfied that the author is much too generous towards the chain-grate stoker in Table 2, when he admits that 5 per cent of travelling-grate stokers under service conditions may reach 81·9 per cent. efficiency, while in the second column he points out that 85 per cent of boilers may be showing a working effici-

ency of 69·2 per cent. We, on the other hand, express the opinion that the efficiency of the finest and best-manufactured chain-grate-stoker plants under service conditions does not exceed 73 per cent for boiler and economizer, and in the majority of plants is as low as 65 per cent. As already indicated, we secure under commercial operation the high efficiency of approximately 83 per cent, it being very easy to secure a CO_2 reading in the boiler exit gases of 16 per cent with just a trace of combustible gas, and the temperature of the exit gases is on the average 50 degrees F. lower than that of a chain-grate stoker when dealing with the same load. Any station engineer admitting the presence of a large amount of CO_2 in the exit gases of a chain-grate-fired boiler would know, or would very quickly know if he attempted to continue this for more than three or four hours at a time, that the furnace arches would be quite unable to carry their own weight, even where the arches are ventilated, owing to the high temperature to which the brickwork was subjected, and, further, that the metal of the grate would become so hot that operation would be uncomfortable and would lead to early breakdown and acute wear. The plant with which we have been experimenting is of the single-unit type and deals with about 30 tons of fuel per 24-hour day. We find it possible to deal with coal containing as much as 5 per cent of moisture. The manufacturers claim 7 per cent. We can say quite definitely, however, that if 4 per cent of moisture is exceeded the output of the plant is noticeably affected. We are, however, in a peculiar position in that our plant is close to a colliery. The coal is crushed on the power station site and is normally delivered quite dry so that it is quite possible for us, even under difficult conditions, to get all the coal into our bunkers with no more than 1 or 2 per cent of moisture. We agree that the pulverized-fuel system gives great flexibility as regards variety of coal. In our case, however, we find that with a lower grade of fuel there is a tendency for the ash to be deposited on the walls of the furnace and then, when a change with a higher-grade fuel is made, for the ash to be melted off, fall to the bottom of the furnace in a liquid state, and come down sometimes at a greater rate than will enable it to be conveniently dealt with as molten slag, thus causing choking. Even then, the question of handling ash under these conditions on a submerged conveyer is preferable to that of dealing with clinker under similar commercial conditions from travelling-grate stokers on the pneumatic ash-handling system. We normally run our pulverizer on full load and we seldom desire to run it at anything else. During about $3\frac{1}{2}$ years' operation we have not lost one boiler tube. We know, however, that it is quite easy to run the pulverizer at half load and secure good conditions. We also find that stand-by and banking losses are greatly reduced. It is a simple matter to shut the plant down and put it on load again. This cuts out the expensive banking arrangements that are so necessary on travelling-grate stokers. To get our plant on load, we have a torch made of asbestos mounted on the end of a pipe. To this pipe is connected a paraffin supply. Just before starting up the plant, the torch is lighted and placed in the coal stream. The plant is then started up and after about 7–15 minutes, depending upon the grade of coal and its state of dryness, the boiler is able to support combustion, and in less than 5 minutes from that time the furnace has attained full heat. We are of the opinion that it is possible for one man properly to supervise a very much larger steam output from a pulverized-fuel plant than with travelling-grate stokers. There are no furnace slides to slice and keep in order, no gears to grease, no back ends to dump and, in fact, no laborious work whatever in the boiler house. The figures given under the heading of "Power Consumption in the Proportion of the Fuel" appear to us to be abnormally high, as our charges for pulverizing and getting the fuel into the boiler amount to 10d. per ton. We think that it would be more economical to dry fuel before it is put into the furnace, than to pass it into the furnace in a wet state and evaporate the moisture there. It would be interesting to hear what boiler manufacturers have to say as to the treatment to which boilers are sometimes subjected when coal burnt under them contains a high percentage of moisture. In our experience with pulverized fuel, which extends over a period approaching four years, we have been able to carry a load approaching 15 per cent higher on the pulverized-fuel-plant boiler than on other boilers in the station, while some of the travelling-grate stokers are only able to deal with 60 per cent of their normal rating. Provided the dust-fuel plant is considered in the way which it should be and all pipes are properly jointed, the pulverized-fuel plant can be kept in every way as clean as any other plant, and we think that there are no difficulties whatever in the way of preventing this plant from being kept as clean as any other. As regards proper temperature control, the important point to aim at appears to us to be that the furnace must be of very large capacity in relation to the size of the boiler; it is then as easy to regulate the temperature and other conditions as any stoking arrangements can be. We understand that special precautions have to be taken to prevent the danger of explosions with pulverized fuel. We should like to hear what the author has to say under this heading. As may be surmised from the statements already made on the single-unit plant, we have never had the slightest sign of an explosion, or apparently any danger of one. If we withdraw the asbestos-paraffin torch from the furnace before the furnace has got sufficiently warmed up, we have found over and over again that the fire goes out and will not restart itself even when continuously supplied with dust fuel and air in apparently a correct explosive mixture. Our difficulty therefore is to obtain ignition. The author states that it is not convenient to store coal in a pulverized state to a depth of more than 5 or 6 ft. This is about half the depth to which it is safe to store ordinary rough small coal, whether in bunkers or in heaps in the open. We should like the author to confirm this figure. When this plant was first installed, we had trouble due to the dust adhering to the boiler tubes. These boilers being of the horizontal type naturally allow the dust to accumulate very readily. It is probable that the vertical type of boiler would be much more desirable from this point of view. We, however, installed a dust-blowing plant and by turning on the

steam and blowing the dust clear we are able to keep the boiler in a far better condition than is the case with average boilers fired by other methods. The figures for capital costs put forward by the author are very much higher than those with which we have had to deal. On the single-unit plant we find that the capital costs were on the right side compared with stoker gears. The pulverizer to give a duty of 30 tons per 24 hours cost £1 725 at the beginning of 1920, and an electric motor to drive it cost £90. Costs have, of course, been very much reduced since then. We agree with the author that cast-iron economizers are the best. On page 394, the author deals with the question of firing the powdered coal to the bins. We have heard tales of the pipes choking up, thus allowing the fires to go out and, when they have been got away, of the danger of explosions, and the author further points out that the coal is now delivered to the bins by means of screw conveyers. We should be glad to know whether the author thinks that there is any truth in these reports. On the same page he deals with the question of hollow air-column furnace walls. We should be glad to have some details as to the manner in which the air is caused to circulate and whether auxiliary fans are required to force the air in; also what percentage of the total air used for combustion in the furnace is circulated in this manner. We should also be glad if the author would say in his reply if the single-unit plant at Vitry is being installed for each boiler, and, if so, what are the reasons that have led to its adoption. On page 403 the author refers to the high efficiency of 81 per cent, which includes the comparatively heavy stand-by and banking-up losses. We are of the opinion that such a figure as this is quite unattainable. On the same page he sets out the reasons why pulverized fuel gives the decidedly higher efficiency. Among other things, it appears to us to be due to the fact that furnaces are now designed to have a very large capacity, and when a piece of coal 1 cubic inch in size is broken down to pass through a 100-mesh screen and so becomes one million cubes of coal, it will naturally be exposed and so can be brought into contact with the air that is available for combustion much more quickly and readily than can possibly be the case with the travelling-grate stoker. The idea in the past seems to have been to make the furnace as small as possible and to keep the tubes as near to the fire grate as to allow of barely working clearance. Travelling-grate stokers have progressed somewhat since then, but furnaces are still very small. On page 405 the author refers to the unburnt fuel in the ash. Our own experience fully confirms the statement made, that the carbon contained in the ash can be kept to, say, 1 or 2 per cent of fuel contained in the ash. In the succeeding paragraph the author deals with the question of riddlings from travelling-grate stokers. On some such stokers the percentage of riddlings has amounted to as much as 35 per cent of the total coal fired. In the last paragraph on page 405 the author states that mechanical stokers are largely dependent within fine limits on coal of good quality. We would add that some stokers are more dependent than others. On page 414 the author refers to the necessity of using distilled water as far as possible to secure reliability of service. Plants that use distilled water from service condensers are kept in reasonably good order. We have had experience with feed-water evaporators for a period of many years and have found them of great benefit. On the same page the author refers to the risk of the coal taking fire in the horizontal type of revolving drier. We have heard of fires taking place inside the tube mill and of the mill being stopped with the idea of putting out the fire, but before the fire could be got under control the entire mill had collapsed. This would seem to require some explanation.

Dr. J. T. Dunn: I am particularly interested in the circumstance that the very complete installation at Lakeside has been designed as the result of careful scientific investigation into the question. Lakeside is not the first power station of the Milwaukee Electric Railway Co. They had before that a station in Oneida-street, part of which, not originally designed for powdered-fuel firing, was altered and adapted for it. The working of powdered fuel there was subjected to continual close observation and record, and to scientific variations of conditions; and it is as the result of these careful experiments that the Lakeside power station has from its beginning proved such a complete success. Take, for example, the matter of grinding. It used to be stated in the early days of powdered-fuel firing that it was necessary to grind the fuel until at least 95 per cent of it would pass a 100-mesh sieve, and 85 per cent a 200-mesh sieve. This was the usual grinding at Oneida-street; but several tests were run in which the percentages passing a 100-mesh sieve varied from 93 to 89, and those passing a 200-mesh sieve from 70 to 64. With this fuel the efficiency of the boiler and the completeness of the combustion were not distinguishable from the results attained with the normal grinding. The importance of this is seen when we consider the power required for fine grinding. In a number of experiments with the Raymond pulverizer, the ratio of the power required to pulverize a given quantity of coal, first so that the percentages passing the 100-mesh and the 200-mesh screen were 99 and 95, and next 95 and 82, varied with the different sizes of machine from 1·3 to 1·65; and Mr. Atkinson, of the Powdered Fuel Plant Co., found with another type of machine that it required $1\frac{1}{2}$ times as much power to get the percentages 96 and 82, as it did to get 94 and 75. Again, in the matter of drying it was formerly believed that it was necessary to dry the coal down to about 1·5 per cent of moisture, in order to get good results. But at Oneida-street, where the coal was usually dried down to 1·5 to 3·5 per cent, a number of tests were run with the undried coal containing 7·7–8·2 per cent of moisture. In these cases the combustion was quite as complete as with the dried coal, and the loss of efficiency amounted to about 0·7 per cent, a quantity corresponding almost exactly to the amount of heat theoretically needed for the evaporation of the additional moisture. As far as the economy of evaporation goes, it would seem to be more economical thus to evaporate the surplus moisture in the furnace than to use a drier, for the efficiency of the rotary drier at Oneida-street was found to be not more than 25 per cent; but there are, as the author

points out, other considerations, which, in some cases at least, make it advisable to dry the coal. The early driers were all of the rotary type, using a coal-fired furnace to dry the coal, and for the most part a fan to draw the necessary air through the drier. They formed a weak spot in the installation, because without careful and constant supervision there was always the possibility of the coal becoming overheated and either firing or losing some of its volatile combustible constituents. Of late these driers are being superseded by gravity driers similar to that described by the author. These are heated by the flue gases themselves on their way to the stack, and not only prevent the danger of fire or loss just mentioned but also save the whole of the coal (amounting to 1 to 1·5 per cent of the coal dried—say 2 000 tons at Lakeside during the period March 1921 to May 1922, mentioned by the author) used in the furnace of the rotary drier. Experience has shown that the danger of fire or explosion is negligibly small if reasonable care is taken in working. Practically all the explosions which did occur in the earlier days were due either to great carelessness or to want of thought, or occurred in experimental work. Mr. Jackson has told us how difficult he found it, not only to explode but also to ignite his mixture of powdered coal and air; and although it is true that the powdered coal which he uses has so much ash and hence so little volatile matter in it that it approaches the composition of those coal dusts which are allowed to lie on the roadways and on the walls of coal-mine workings, yet the same thing has been shown to be true with coals that are much more readily combustible. I agree with the author as to the confusion which exists due to the lack of definiteness in the expression of units in records of numerical tests. It is greatly to be desired that the use of the so-called "net" or "lower" calorific value of combustibles should disappear, for it has no useful significance. I would go further than the author here, and say that we shall never have satisfaction in this respect until our cumbrous British units have disappeared and all our records are kept in metric units. The author refers to the radiation from the heated particles of ash in the furnace. This is really an important aid to the ready transmission of heat to the boiler tubes; and where blast-furnace gas is used along with powdered coal, as in the large Ford installation described in the paper, and as at the Park Gate steel-works at Rotherham on a small scale, the transmission of heat from the blast-furnace gases is found to be sensibly increased by the presence at the same time of the ignited powdered fuel. In regard to no-load losses, there is a very interesting record from the Oneida-street tests, in which the boiler ceased work at 9 p.m. and work was not resumed until 7 a.m. the next day. The loss of pressure during that time was only from 175 to 155, or 20 lb. per sq. inch, although between 9 p.m. and 11 p.m. the safety valve was released for 15 separate minutes. A great deal has been made of the nuisance caused by the ash from powdered-fuel installations, and of the difficulty of dealing with it. At Lakeside and in other installations this difficulty has been altogether overcome; and in different ways, as Mr. Jackson has stated, the same difficulties have been surmounted elsewhere. Where a large quantity of the ash escapes from the chimney it is in such an extremely minute state of division that it falls exceedingly slowly, and is distributed by the natural currents in the air over such a wide surface before it reaches the earth that it is never discoverable. The emission of this fine dust from a chimney is entirely different from the emission of grits (even though these may be completely burnt) such as are ejected from the chimney in the case of mechanical-stoker firing, and the dimensions of which are enormously greater than those of the particles of ash from powdered fuel.

Mr. A. R. Clemitson: If the system of powdered fuel becomes established in this country then mechanical stokers will not be required, and while water-tube boilers with horizontal tubes may be used with this system it is obvious that its application is more readily adapted to vertical-tube boilers. As the correctness of figures is so important in making comparisons of efficiency I should like to draw the author's attention to the following: In Table 7, Test 1, the efficiency of boiler and superheater is stated to be 83·3 per cent and with the economizer 86·3 per cent, a difference of only 3 per cent, while the temperature of the gases leaving the boiler are 434° F. and after the economizer 168° F. This drop in temperature should account for about three times the above difference. In Table 8, test 1, item 36, the temperature of the gases leaving the boiler is given as 434° F. and entering the economizer 338° F. What is the reason for this big loss, as apparently the gases enter the economizer immediately after leaving the boiler? In item 38 the temperature of the gases leaving the economizer is very low and in one case only 168° F. If this is correct what effect has this low temperature on the economizer tubes, and does the moisture present any difficulty? On page 400 attention is drawn to the enormous size of the combustion chamber required for powdered fuel, and it is stated that at least 1 cubic foot of space is required for every 3 lb. of coal burnt per hour. This figure appears to be a very conservative one and provides a combustion chamber area very little larger than should be provided in a well-designed chamber with mechanical stokers. I should have considered that 0·8 to 1 cubic foot per pound of coal would have been more desirable. On page 405 the author points out that a high percentage of CO_2 can be obtained with powdered fuel, "which means a continual high temperature of combustion averaging over 2 000° F.", but surely he does not consider this temperature high for powdered fuel, as it would be considered low for mechanical stokers and could not give the high-efficiency results claimed for either system. The figure should be nearer 3 000° F. The author has made out a very good case for powdered fuel, and against the many advantages of this system the only extra cost is the power required for crushing the coal. The principle of admitting air through the brick walls is a good one as it must increase the life of the brickwork while at the same time reducing the radiation losses and adding considerably to efficient combustion. This method could not be so satisfactorily applied to mechanical stokers. With reference to the drying of coal, it would appear to be a more reasonable method to remove

the moisture outside the furnace than within. In the latter case it is evaporated by the heat from the coal and goes away with the gases as superheated steam which is all lost heat. The system of drying the coal with waste gases adds considerably to the overall efficiency of the plant and eliminates the dangers of some of the other methods of drying. The utilization of waste gases for heating the air for mechanical stokers has been applied, but it cannot be considered to be a great success with most stokers as the burning of the bars is excessive. The trouble with ash from the chimney and the large amount of dust which finds its way into the boiler tubes requires consideration. No doubt some form of collector could be satisfactorily arranged in the chimney, if necessary, but it is not likely that there will be more trouble from this than in the case of mechanical stokers, where a great deal of grit and smuts is emitted from the chimney. I do not readily understand the author's preference for the central system over the unit system. With the latter the capital cost is much less and brings it into favourable comparison with mechanical stokers, while the dangers from explosions and fires would be entirely eliminated. While it may be contended that the danger from this source with the central system is not frequent, yet it should not exist at all if it can be readily avoided, as it can be in the unit system. It is a much simpler arrangement to deliver the powdered fuel direct to the boiler, as in the case of the unit system, than to pass it through a separator, then into a bunker and then to feed it into the boiler, an arrangement which is unnecessarily complicated. I should be glad if the author would state whether coke alone can be used with the Lopulco system; whether the system has been adapted for boilers on board ship; and whether it is suitable for this purpose. The desirability of coming to the right decision on this subject is most important and it is unfortunate that we have not a national system to investigate these methods, as it is only by extensive tests with coal used in this country that we can expect to find the best system for our own particular use.

[The author's reply to this discussion will be found on page 460.]

East Midland Sub-Centre, at Loughborough, 29 January, 1924.

Mr. E. G. Phillips: I should like to know if means have now been provided to prevent the pulverized coal from taking on the "liquid" form and passing through the feeding screw conveyers as though no impediment existed. In the cement industry, where this class of fuel has been used for 20 years, this trouble occurs without warning. I have known everything to work satisfactorily for months, and then suddenly, without any apparent reason, the whole of a 50- or a 100-ton bunker will be emptied in a few minutes by the whole of the material passing through and over the screw and dumping itself on the ground. Has the graduated pitch of the conveyers shown on the screen been designed to overcome this trouble? In view of the entire absence of any British information, I should like to know if the author can give any information of the one fairly large pulverizing plant in this country, i.e. Hammersmith, which has now been running for a sufficient period for some data to be available.

Mr. T. P. Wilmshurst: I am disappointed that the author refers to only one system of burning pulverized fuel and confines himself to very large plants, whereas plants of, say, 20 000 to 40 000 kW are much more common in this country. I consider that the comparison of the large boiler plants at Rouge River and Lakeside with their boilers of 26 470 and 13 060 sq. ft. heating surface respectively, with the Dalmarnock boilers of 6 948 sq. ft. is hardly fair; further, the American coal contained 12 000 to 13 000 B.Th.U.'s as against Scotch coal of 9 900 B.Th.U.'s. There is also the difference in the combustion chambers and the use of preheated air to consider. I should prefer to hear less of the overall efficiency of the boiler, and more of the total commercial cost of running per unit generated or sent out—such figures to include all capital charges and the cost of running auxiliaries. I recognize the excellent features of the pulverized-fuel plant, and have a perfectly open mind. In this connection I may say that in Derby we shall shortly put down two or three large boilers, each of 60 000 to 80 000 lb. evaporation, and any thoroughly commercial scheme will receive the most careful consideration.

Mr. G. H. Rutland: Can the author give any information as to the application of the pulverized-fuel system to marine work? I believe that experiments were made some years ago. The fuel was, I think, pulverized on shore and stored on the ship. This necessitated special bunkers and I believe that the fuel absorbed moisture from the air and clogged in the conveying system. With regard to the question of the wear on the burners, there must be a good deal of grinding action and it would seem that the smaller portions of the burners would rapidly enlarge and so lead to inefficient burning of the fuel. I raise this point after experience with unfiltered oil in oil-fired boilers. In this case the wear due to grit in the oil rapidly throws the burner out of adjustment when the high-pressure system is used. The question of the ash ejected as dust would appear to be worth considering. We know that even an impalpable powder can be used in some grinding processes, and surely the fine ash that is ejected into the air may cause trouble in other works' plants if not in the immediate vicinity of the station. With oil-fired boilers we are sometimes troubled with what is called the organ-pipe effect. A pulsation in the air admitted to the furnace sets up powerful vibrations in the whole of the gases in the combustion space and uptakes. A small change in the oil or in the uptake or in the amount of air may or may not stop the trouble. As the pulverized system of firing is very analogous to the oil-fuel system, I should like to know if any similar effect has been noticed with this system. If it did occur the vibrations would possibly have a very serious effect on the water screen which is a feature of the

Lopulco system, especially if the period of the screen were in tune with that of the air. The size of the boilers used to generate the power is spoken of with pride, but I would suggest that there seems to be a good deal of space wasted. In marine practice it is common to find boilers which can deliver 43 000 h.p. at the shafts, together with all their fuel and water pumps, forced-draught fans, etc., stowed in a total space of 100 ft. × 29 ft. × 18 ft. Site value should be worth considering and, in my opinion, steps should be taken to see what economies in space could be made with power station plant.

Mr. F. Nicholls: In his comparison of Lakeside and Dalmarnock the author gives the difference in the average CO_2 percentage obtaining in the flue gases as 15 to 17 per cent at Lakeside and 10 per cent at Dalmarnock, and I would suggest that the large difference is due not so much to using powdered fuel as to the much larger combustion chambers in use. Operating engineers in this country know that with the mechanical stoker when aiming for more than 13 to 14 per cent CO_2 there is danger of CO formation and consequent loss of temperature and efficiency, and I suggest that without pulverizing, given greater combustion space, the correct fusion of air and combustible would take place before striking the tube surfaces, as is at present the case. Preheating the air supply at Lakeside is an added factor towards its higher efficiency, and it would appear that boiler-makers in this country will have to tackle this question, as it is certain that higher temperatures can be used. I was particularly interested in the final exit gas temperatures obtaining at Lakeside, and on one test the figure of 168° F. struck me as being remarkably low for the corresponding water temperature. I should be glad if the author would state the size of economizers in use in America. One great advantage of powdered-fuel firing would appear to be the quick response to any alteration in conditions, also the ease of control of excess air admission, thus following on the lines of oil-fuel firing. I would suggest that the comparatively low efficiency figure quoted by the author for boiler plants in this country, viz. 69 per cent, is largely due to scale formation in tubes, and that the more extended use of distilling plants for making up losses will obviate this with a consequent increase in efficiency.

Mr. S. J. R. Allwood: Owing to the inability to obtain the desired superheat with the usual type of integral superheater, there has been designed a radiant-heat superheater in the form of cast-steel headers built in the furnace wall. I should like to know if the author has had any experience of these, and, if so, what kind of trouble is experienced with them. I suggest that the water screen, unless particular attention be given to the purity of the water, introduces a very weak point in the boiler. I consider that the author has made out a very good case for the efficiency and flexibility of this method of firing, but not so convincing a one on the question of the comparative cost.

Mr. D. Rushworth: On page 393 the author refers to the question of steel versus cast-iron fuel economizers. In this connection Sir James Kemnal at the London meeting said that in his opinion "the cast-iron economizer has been an excellent servant, but the pressures that are common nowadays render it less suitable." Also, "there are too many cases of cast-iron economizers being replaced by steel economizers for the author's assertion to be taken as representing altogether the facts of the present day." Speaking as an engineer who has had 38 years' practical experience with the Green-type cast-iron fuel economizer, I agree entirely with the author's statement and disagree with Sir James Kemnal's remarks. In the first place it would be interesting to know why the important power stations run by the Corporations of Birmingham and Leicester should have decided within the past few months to install cast iron as a protection against the corrosion which has taken place with the steel-tube economizers of which they have had experience. I could give numerous instances of steel tubes having failed after a few years' working. As the author points out, cast-iron economizers can now be made to withstand the highest pressures, thanks to improvements in their construction, either by the method advocated by the author or in the method of manufacture. It is without doubt that cast iron has proved to be superior to any other material for economizer construction, and economizers have been known to be in service after working 35 years: no steel economizer could lay claim to such a record.

Mr. J. Cauthery: The figures of running efficiency obtained at Lakeside are certainly very remarkable, and are a challenge to the mechanical stoker. It is, however, necessary to have, as pointed out by Mr. Wilmshurst, figures showing the price at which this efficiency has been obtained, with all costs and charges taken into consideration. Reliability—by which is meant freedom from breakdown and continuity of running—comes first, and it is desirable that more and fuller particulars should be given on this point. The author mentions a boiler being run for 9 months on end with pulverized fuel at the Ford works. Is such a run a common feature with boilers fired by powdered-fuel plants, or is it a sort of feat and so not to be taken as an average? Having regard to the number of stages through which the fuel has to go before it is ready to be blown into the furnace, and the mechanisms and storages on the way, it would seem that in the nature of things there must be a greater liability of breakdown at one point or another than with mechanical stokers. The water screens may increase the possibility of trouble by overheating, contraction and expansion, and it would be well to know if any trouble has resulted from them. The rupture of one of these tubes and the sudden emptying of one of these mammoth boilers might result in a considerable disaster. The last word has not yet been said with regard to the mechanical stoker. Test efficiencies of 85 to 87 per cent have been obtained with them, and there seems no reason why with the improvements now being made a much higher day-in and day-out efficiency should not be obtained.

Professor C. H. Bulleid: I should be glad if the author would give some information as to the application of the system to small stations and small boilers. In the aggregate these account for a very large part of the total amount of coal burnt per annum. With

regard to the fine ash blown out of the top of the chimney, whilst agreeing that it is not an immediate nuisance I should like some information as to its ultimate effect on vegetation, and should be interested to know if it chokes up rain-water spouting. In connection with the trouble found in connection with the fusing of the ash, is it not possible to make a virtue of necessity and arrange that the ash should fuse completely and should then be run out through a slag hole?

[The author's reply to this discussion will be found on page 460.]

South Midland Centre, at Birmingham, 30 January, 1924.

Mr. F. Forrest: The undoubted success which has attended the use of pulverized fuel for the firing of steam boilers is really due partly to the pulverizing of the fuel and partly to the large combustion chamber which it has been found desirable to install when using this class of fuel. In Table 2 the author is rather unfair to the mechanical stoker, in so far as he has compared the results obtained when using pulverized fuel in an ample combustion chamber, with those obtained on the old type of mechanical stokers having cramped combustion chambers. It would be interesting if he could give results obtained with pulverized fuel used on a boiler fitted with smaller combustion chambers of the size usually put in when mechanical stokers are used, so as to show to what extent efficiency depends upon furnace design and to what extent it depends upon pulverizing. This question of large combustion space has not hitherto received the attention that it deserves, and I suggest that every boiler installation should be compared on the basis of the cubic feet of combustion-chamber space provided for each pound of coal fired to the grate per hour; in other words, we should compare the space provided for the complete combustion of a certain quantity of gas per hour in the two systems respectively. The following figures obtained from various large power stations using water-tube boilers fitted with mechanical stokers show how this figure varies in this country and abroad:—

	Lb. of coal burnt per hour per cubic foot of combustion space
Average British practice	3·6 to 6·2
Dunston (Yarrow boiler)	3·5
Gennevilliers (Paris)	1·93 to 3·05
Philadelphia (U.S.A.)	1·22
Calumet (U.S.A.)	1·52

With pulverized-fuel plants the figures are as follows:—

	Lb. per cubic foot
Lakeside (U.S.A.)	0·85 to 1·39
River Rouge (Ford)	1·49
Figure recommended by Kreisinger .	1·0 to 1·5
Maximum recommended by author .	3·0

The compartment type of mechanical stoker is a very great improvement on anything produced hitherto, and such a stoker combined with ample combustion space would give a flexibility in the choice of fuel and a furnace efficiency approaching that obtained with pulverized fuel. With such a stoker full duty has been easily obtainable with gasworks coke-dust burnt alone, the fuel having a calorific value of about 10 000 B.Th.U.'s per lb., with only 5 per cent of volatile matter. The author does not state to what extent the size and cost of boiler-house building would have to be increased in order to accommodate the pulverized-fuel plant, as compared with the figures for mechanical-stoker plant. It seems to me that a larger and more expensive building would be necessary with the former, and this additional capital expenditure should be taken into account when comparing the total cost of steam generated in the boiler house with the two systems. The highest boiler-house efficiency is not, however, the only consideration. What is of greater importance is the lowest cost of steam per unit generated, including all fuel costs, operating and maintenance costs, and capital charges. With ordinary unwashed slack coal at less than 15s. per ton delivered, it would be very difficult to make out a case for a pulverizing plant, but the burning of more expensive fuels in pulverized form would probably show a saving over the usual method of burning it on mechanical stokers. Can the author mention a really satisfactory CO_2 indicator or recorder for use in the boiler house? We have tried in Birmingham almost every type made, and the only one that is at all satisfactory from the point of view of continued accuracy and with the minimum of time-lag between taking the sample and indicating the result, is the electrical type of indicator produced by the Cambridge and Paul Instrument Company, and even this requires further improvement before it can be regarded as an accurate and robust boiler-house instrument.

Mr. F. C. Platt: In Great Britain we appear to lack courage in the steam-raising department, although in the engine room we have not hesitated to keep well up to the practice of less conservative countries. We cling to the comparatively small boiler, and rows of such boilers with their attendant ranges of steam and feed piping are necessary to make provision for the large steam demand in a modern station. We should strive to replace all these small units with large units capable of being kept under steam for very long periods, and sufficiently reliable to be kept in commission from one annual inspection to another without serious breakdown. The problem of firing such boilers seems to call for drastic action. In my opinion, to ensure the reliability and length of operation previously mentioned we must, for one thing, get rid of the ponderous mass of machinery which mechanical stoking involves. Even our comparatively small boilers, evaporating, say, 50 000 lb. per hour, require the chain-grate stoker to be divided into three parts, whilst the somewhat larger boilers at Gennevilliers have to be fired from both sides. With pulverized fuel vast quantities of heat can be generated in the combustion chamber of the boiler, with an entire absence of machinery at the boiler itself.

Perry, in his book on "The Steam Engine and Gas and Oil Engines" (1904), states that "the fixed carbon needs to be scrubbed with air." With the mechanical stoker we are accustomed to burn very finely divided coal, and the quality known as "washed fine" is very popular. Here is an attempt to utilize the idea outlined by Perry, but with pulverized fuel we can achieve in a practically perfect manner the scrubbing of each particle of fuel with air. An important aspect of pulverizing plant is that it can be worked at a load factor irrespective of the boiler load factor at any given time, i.e. the load factor of the pulverizer plant is independent, within limits, of the load factor of the boiler which it serves. The amount of storage capacity would also give a 10–15 hour period for repairs to be made to the pulverizing plant, whereas if the mechanical stoker is not in operation there is no steam. The objection on the score of fine ash emitted from the chimneys of boilers using pulverized fuel is of little moment, as far worse results are obtained with chain-grate stokers burning fine slacks. In one plant under my charge, one chimney discharging gases from two 20 000-lb.-per-hour boilers, which work at full load only for an eight-hour day, has rendered necessary the cleaning out of all the gutters in an extensive area of roof adjacent to the power station, after the short interval of five weeks.

Dr. W. Lulofs: The general impression which I have gained is that the author exaggerates the advantages and attributes to powdered fuel virtues which it cannot strictly claim. The manner in which he attempts to prove the superiority of the powdered fuel system over the chain-grate stoker by comparing the practical results obtained in various stations is open to criticism. A direct comparison of the nature of the two systems leads more directly to the same results. Bearing in mind that the combustion of the coal is merely a chemical reaction between the oxygen of the air and the carbon, hydrogen, etc., of the coal, the conditions under which this chemical process takes place must be far less ideal in the case of the mechanical stoker. As the coal burns away steadily on the mechanical chain grate while it is being carried through the furnace, leaving only the ash at the end, the thickness of the layer of coal along the grate gradually diminishes towards the back and the quality of the fuel diminishes correspondingly. The effect of this is—assuming an equal draught over the whole stoker—that the ratio of quantity of air per lb. of combustible matter varies considerably along the grate, causing an excess of air at the end of the stoker. In addition, the stoker at this end has to deal with very inferior quality of coal containing no volatile constituent, and an increasing percentage of ash, theoretically up to 100 per cent. This results in a low percentage of CO_2 at this end of the stoker (on an average not more than 5 per cent) and a great difficulty in burning the coal completely. There are thus two sources of loss. First, the uneven distribution of air makes it impossible to run at a high average of CO_2 without CO; indeed, this is the explanation of the fact that, as mentioned by the author, with the mechanical stoker not more than 13–14 per cent of CO_2 can be obtained without CO, whereas with powdered fuel 16–17 per cent may be obtained. The other loss is a certain percentage of carbon left in the ash, also due to the cooling effect which the boiler has on the grate, 5 per cent of carbon on an average being a low figure. Owing to the defects inherent to the mechanical stoker much skill is required to operate it efficiently, and the extra attendance necessary adds to the loss. In addition, there are extra stand-by and starting-up losses on account of the lack of adaptability of the chain-grate stoker to variations in the load and the considerable period that elapses from starting up to an efficient running condition. The manufacturers of chain-grate stokers have brought out devices to counteract these defects. In consequence the compartment stoker has been evolved which allows for the regulation of the air, in sections, underneath the stoker. This enables the amount of air per lb. of fuel to be regulated throughout the length of the stoker. Adjustable dumping bars or dams have been designed in order to bank up the fuel at the back of the stoker, thus causing a thicker layer and by this means decreasing the excess of air. A back arch has been constructed for increasing the temperature in order to assist the combustion of this poor fuel. Although improvements have thus been obtained, they have tended to camouflage rather than eliminate the original defects, and therefore the system of powdered-fuel firing remains superior. On the other hand, the advantages of powdered fuel over chain-grate firing are not so considerable as to cause existing chain-grate stokers to be completely superseded, especially as the changing over to powdered fuel would necessitate a much larger combustion chamber and therefore a complete re-setting of the boilers. In view of the enormous number of chain-grate stokers in daily use it may prove of value to point out how the adoption of powdered fuel in combination with existing mechanical stokers can reduce the above-mentioned principal defects and so bring the mechanical stoker more up to the standard of powdered-fuel firing. At the same time this combination may overcome some of the difficulties met with in the latter method of firing. The Underfeed Stoker Company have effected this combination by inserting a number of small burners (or jets) of powdered fuel at the back of the stoker in such a manner that a row of small flames from these burners is directed almost parallel to the mechanical grate but pointing slightly towards it. This results in three distinct advantages over the mechanical stoker alone, viz. (A) increased efficiency, (B) increased boiler evaporation, and (C) increased adaptability for a varying load. As regards (A), (1) the row of small flames acts as a perfect form of back arch with all its advantages and none of its disadvantages, especially in respect to the upkeep and repair of brickwork. (2) The amount of excess air at the back of the mechanical stoker is utilized for completing the combustion of this powdered fuel by regulating the amount of air supplied in the mixture to the burners. (3) As the flames from the burners are at right angles to the flames from the mechanical stoker a whirling motion is set up in the combustion chamber and brings the excess air and combustible matter into close contact with one another. As regards (B), increased evaporation is

obtained, due not only to the increased amount of B.Th.U.'s set free from the combustion of the powdered fuel but also to a higher temperature in the combustion chamber. In addition, more fuel can be burnt per sq. ft. of grate surface. The boiler is enabled to absorb these extra B.Th.U.'s because of this higher temperature, which also accounts for the fact that the temperature of the superheated steam is not increased by the higher temperature in the combustion chamber. Actual tests have proved that with a 20 per cent increased evaporation the rise in temperature of the exit gases from the economizer was practically negligible. A 30 per cent increase of evaporation was reached but could not be continued because the boiler commenced to prime. As regards (C), by this means the evaporation can be instantaneously adjusted by regulating the supply of powdered fuel, and further, the boiler takes considerably less time to start up because the powdered-fuel flames, once started, raise the temperature of the brickwork and the combustion chamber very rapidly. On the other hand the mechanical stoker will assist the powdered-fuel firing, because the ignition is always certain and because the ash from the latter falls on to the mechanical stoker which then removes it. It will be obvious from (B) and (C) above that the adoption of powdered fuel has the further advantage that the steam production of an existing boiler house may be thus increased without any extension of boilers being necessary. In this connection I should like to mention a further advantage of powdered fuel in general which the author does not appear to emphasize sufficiently. The development of station design tends towards the use of ever-increasing sizes of boiler units, and the bigger the boiler the greater the difficulty of supplying adequate grate surface (which I regard as the heating surface of the boiler). One of the many things which one is taught in theory and discovers later to be wrong in practice is the manner of describing the various functions of the different parts of which a boiler unit is composed. In my opinion the boiler proper has only a cooling surface, the heating surface of the boiler being the grate surface and, therefore, for a certain boiler the heating surface must be such that it can produce that number of heat units which that particular boiler is capable of absorbing. Since the number of heat units which a square foot of grate surface can liberate is limited, there must be a fixed proportion between boiler cooling-surface and grate heating-surface. Where the cooling surface of the boiler is not, as is the grate surface, restricted to the floor space, it is obvious that by increasing the cooling surface of the boiler the difficulty of providing adequate heating surface increases accordingly and is ultimately insurmountable. Here the adoption of powdered fuel comes to the rescue. First, the heating surface is now no longer restricted to floor space and can therefore keep step with the increase in cooling surface of the boiler; and, secondly, the temperature of the combustion chamber can be raised through which the cooling surface of the boiler becomes more efficient, which means that for a certain duty the dimensions of the boiler unit can be decreased.

Mr. W. Wilson: The system of pulverized firing described by the author is interesting for several reasons. The process seems to be very well thought-out and to be in every part exactly suited for its functions. The pulverizing of a soft material such as coal, even to the fineness of a 200-mesh screen, need not be an expensive matter if suitable apparatus is employed, as is instanced by the economy of the cyanide process for the extraction of gold from quartz. The roller mill and conical separator employed in the plant described in the paper remind me forcibly of the usual apparatus employed in the case of the gold ores; and the method exhibits every probability of doing the work efficiently and economically. The beauty of the pulverizing principle is that it converts the fuel into a form that can be treated as a gas and can be consumed in a Bunsen burner. The completeness of the combustion obtained by the latter device is proverbial, and should render it possible for this mode of boiler firing to achieve maximum efficiency. It is not unnatural that such a method has not been developed in this country, since good coal is available for practically every power station. In some countries, however, lignite and other poor forms of coal are the rule rather than the exception, and under these conditions pulverized combustion will show to greater advantage. In this connection I should like to ask the author if peat has been so treated, as there are large and valuable deposits of this fuel in Scotland that should be open for utilization in this form. Two of the drawbacks of the system that have been mentioned do not appear to me to be serious. It is not correct to say that powdered coal is explosive, at any rate in the same way as gunpowder. The coal needs to be mixed with air before an explosion is possible, and it is only necessary to prevent leakage of the powdered material in order to render it safe. Ordinary wheat flour suffers from exactly the same drawback, and serious explosions have been caused in the past by carelessness in handling it. Finally, ash in the chimney gases should not be troublesome in practice, since the particles of coal are already reduced to a fineness of about 1/200 in., and after they have been burnt all but between 2 and 5 per cent is removed in the majority of coals. Thus the resultant particles should not be larger than about 1/1 000 in., a size comparable with that of the motes which are seen floating in every sunbeam.

Mr. C. H. Petford: The author refers to the great difficulties in the way of comparing two entirely different systems of firing, i.e. pulverized fuel and mechanical stoking. In view of this statement it is surprising to find that he has rather added to the difficulty of comparison by dealing with English test-results in English units and with American test-results in American units. I consider that the author could have made Table 9 much clearer if, instead of dealing with the operating costs of the American plant in American units, he had applied English rates of wages as are at present being paid in this country. He should have had no difficulty in this direction with his knowledge of the class of man required to carry out the various classes of work demanded on a pulverized-fuel station. Had this been done, a direct comparison of labour charges on the two different systems of firing would have resulted, and it would have brought to light a point which requires

some little explanation, for in Table 9 the author gives the pulverizer-house operating charges as 18·8 cents per American ton (this includes all conveyer attendance, etc.) and on page 410 it is stated that 0·465 dollar per American ton corresponds to 25d. per English ton, on the basis of American wages, and that this would equal 14d. per English ton on the basis of English wages. 18·8 cents per American ton on the American wage basis would then be equal to 5·66d. per English ton on the basis of English wages by the author's own method of comparison. If this cost of coal-handling is compared with the coal-handling charges for Dalmarnock referred to in Table 16, one sees that for Dalmarnock for the month of March 1923, over which period a little more fuel was handled than referred to with regard to the American pulverizer-house charges—therefore forming a fairly rational comparison—the coal-handling plant-operating charges were 0·0052d. per unit delivered, and, by calculation from the other data given in the table, the fuel-handling charges at Dalmarnock become equivalent to 5·87d. per ton, so that it costs more in labour charges for Dalmarnock to unload the fuel and convey it direct to the bunker than it does for the Americans (on the English basis) to unload the fuel, convey it to a coarse coal bunker, grind it, convey it to the powdered-fuel bunker, and from thence to the boilers. This would suggest that there is either something wrong with the systems of handling fuel in this country, or that some satisfactory explanation should be provided. The author's method of comparison on the wage basis is not entirely satisfactory. The average wage for the class of man required in a pulverizer house in this country could, I think, be taken at the outside as 15d. per hour. Working on this basis, complications resulting from rates of exchange and relative wage basis are avoided, and taking from Table 9 that 4 567 hours (total) are worked in the pulverizer house on 13 670 tons (English) then at an average rate of 15d. per hour the pulverizer-house charges in this country would be equal to 5·0d. per ton of fuel handled. This makes the comparison with Dalmarnock considerably worse. The author's statement with regard to the high efficiencies that could be obtained with pulverized-fuel firing is, I think, universally agreed by engineers, but efficiency is only one of the factors necessary for economy and in many cases the straining after the higher efficiencies often results in lowering the overall economy, due to additional charges. Here we have less charges and higher efficiency, however, but I fail to see how the handling charges of the fuel for the many operations required in the pulverizing plant can be less than the charges for direct conveyance to bunker. Dealing with fine ash blown into the atmosphere, the author states on page 415 that on the average about 17½ per cent of the ash seems to be discharged from the chimney top. On this basis, then, Dalmarnock for the month of March, 1923, with powdered-fuel plant installed would have sent out about 360 tons of fine dust into the atmosphere, and, although it may be in the state of a fine powder, I am afraid that the medical authorities in this country would not look upon it with favour. I cannot altogether agree with his statement that there should be no more difficulty in preventing the emission of this fine ash from the chimney than with any other method of firing, for I think that the very fineness of the particles will in itself increase the difficulty of trapping it. With regard to the statement that on the recent careful test in the United States it was discovered that with mechanical stoking no less than an equivalent of 3 per cent of the coal fire was discharged from the chimney top, it seems difficult to believe that such a thing could possibly be taking place in this country, for 3 per cent with a fuel which contained on analysis 15 per cent of ash would mean that 20 per cent of the ash was ejected to the atmosphere, in this case in the form of detectable grits. With regard to furnace brickwork, it would be interesting to know what is the relative cost of the brickwork in a pulverized-fuel plant as compared with that used in mechanical-stoking practice. The initial cost in the former, due to its considerable size and possibly special bricks, will be high, and, although it may last for three years without any renewals, what will the cost of such renewals be? It would appear that in the long run the renewals will be a much more expensive item than is at present the case with mechanical stokers.

[The author's reply to this discussion will be found on page 460.]

North Midland Centre, at Leeds, 5 February, 1924.

Mr. M. Wadeson: Although the author gives the reasons why he has dealt only with the Lopulco system, I think that the value of the paper would have been increased if a description of other pulverized-fuel systems had been included. There is no doubt that pulverized fuel can be most efficient; combustion is, after all, a chemical process, and no effort to combine a solid and a gas can be so efficient as when the former is reduced to an impalpable powder. Moreover, the large combustion chamber is a further factor tending to efficiency, but efficiencies equivalent to that obtained by the use of pulverized fuel can be obtained, and already have been obtained, by other methods, e.g. the gasification of the fuel before burning. The author states that the paper is essentially a comparison between a pulverized-fuel station and a mechanical-stoker station. He has taken Dalmarnock because he was able to get the figures for that station, but Dalmarnock has not the highest boiler-house efficiency of stations in the United Kingdom. Many details of the process of pulverized fuel can be applied to mechanical stoking, e.g. as the heating of air and the use of a large combustion chamber, and I think that the adoption of such portions of the pulverized-coal process will undoubtedly raise the efficiency of mechanical stoking somewhere in the neighbourhood of the pulverized-fuel process. The author mentions that only 5 per cent of the stations in the British Isles had an efficiency of over 75 per cent, but I am of the opinion that this is a low figure. He gives 85 per cent as the realized efficiency

for pulverized fuel, and quotes high guaranteed figures which have not yet been realized. As he points out, however, efficiency is not the only factor. I take it that the author does not suggest that the power stations in the British Isles should scrap their plant, but rather that pulverization should be adopted in the new stations where circumstances warrant. As to its adoption in new stations, it would depend entirely on whether the stations were of sufficient size to warrant the use of pulverized fuel, and also on other questions in connection with it. The author states that the actual costs are considerably greater in small stations. That must be obvious, as is shown at the end of the paper where the height of the boiler house in one station is given as equivalent to the total height of the chimney in the other. The height of the chimney in the pulverized-fuel station is about 2¾ times the height of the chimney in the mechanical-stoker station. The author states that the drying temperature is regulated at 215° F. I should like to know how that regulation is carried out. If the boiler is forced, the temperature of the exit flue gases will be higher and more air will have to be admitted to bring down the temperature to the requisite amount. I believe it to be a fact that fine dust accumulates in the boiler tubes, and it is often of advantage to use a dust blower at frequent intervals. The author appears to assume throughout the paper that the British engineer is backward and conservative against his own interests. It is a charge which has been levelled many times. In connection with large turbines I believe it was said that the British engineer was backward and conservative, but I strongly dissent from this view. The British engineer may be cautious, but I do not think that he is over cautious.

Mr. J. W. J. Townley: I do not think that anyone will disagree with the contention that pulverized-fuel firing will give more efficient combustion and can be more easily controlled than any other system of burning coal, but in considering this matter I would suggest that the question is not one of thermal efficiency alone. Thermal efficiency is not necessarily commercial efficiency, and a 1 per cent improvement in boiler thermal efficiency may not be thought worth while when the cost of obtaining this is taken into consideration. The first problem that one usually has to consider is the case of the existing plant and whether it is worth while to change over from stokers to pulverized fuel. I have studied this matter recently, and have considered the conversion to pulverized fuel of a battery of three 35 000 lb.-per-hour boilers. These boilers are equipped with chain-grate stokers and burn a rough slack costing (at present) 17s. per ton. The actual efficiency upon a series of 10-hour tests averaged 81·5 per cent, based on the gross calorific value of the coal as fired. The actual total amount of coal burnt per annum is 18 000 tons, the load factor being 33 per cent. If by the adoption of pulverized-fuel firing we can obtain an increase of 4 per cent in the overall efficiency, then the saving in fuel would be 900 tons, which at 17s. per ton is equivalent to £765 per annum. The cost of a 7-ton-per-hour pulverized-fuel plant (including alterations to combustion chambers) based on recent quotations would be £16 000. Annual charges (interest and sinking fund) assuming a 20-years' life, would be £1 315, or a net extra cost for capital charges alone of £550. The power required by the auxiliaries would be slightly greater for the pulverized-fuel plant but not sufficiently so as to have any material effect upon the above results. Secondly, the case when stoker replacements are due may be considered. The cost of six stokers completely equipped and erected would not exceed £6 500. Annual charges would amount to £535, as compared with the capital charges of £1 315 for the pulverized-fuel plant. The difference, £780, would more than cancel the saving in fuel of £765. It can be seen, however, that in this case there is a very narrow margin, and that the choice of firing plant may be decided by such factors as variability in the quality, low calorific value, and cost of the fuel which is available. It would appear, too, that it is possible to maintain a higher annual efficiency with pulverized-fuel plant than with stoker plant, owing to the ease of control. Most users know only too well the very great difficulty in maintaining a high efficiency of stoker plant at times of light load. I do not agree with the author that the actual cost of current for auxiliaries for the pulverized-fuel plant is the same as that for mechanical stokers. It is generally agreed that the power required for the operation of the pulverizing and drying plant amounts to from 20 to 25 units per ton of fuel. That is equal to 0·55 per cent of the boiler-plant output, assuming 15 lb. of steam per kWh. Comparing this with a forced-draught chain-grate stoker, I find that the forced-draught stoker takes only 3·5 units per ton on normal load, equal to 0·1 per cent of the output, or, allowing for light loads, say 0·15 per cent. The other auxiliaries are common to both systems, although the power required for the induced-draught fans may be considerably reduced owing to the smaller amount of flue gases in the case of fuel firing. Some of the comparisons in the paper are not quite fair; for instance, in the particulars given of the tests made upon the Colfax boiler plant, no reference is made to the fact that this plant is not fitted with economizers, and the comparison between Lakeside and Glasgow is affected by the much lower load factor at Glasgow and the larger heating surface of the Lakeside units. Our principal source of information with regard to pulverized-fuel firing for steam boilers is the United States, but American engineers are not by any means of one mind regarding this method. In a list of 37 plants under construction given in *Power* (31 July, 1923) 29 of these are being fitted with stokers and 8 with pulverized-fuel plant. In the 1923 Report of the Prime Movers' Committee to the National Electric Light Association there is a statement by the Puget Sound Power Company that their pulverized-fuel plant costs 3¼ cents more per 1 000 lb. of steam than another station fitted with chain-grate stokers, although in the case of the former the cost per ton of the fuel used is 29·3 per cent less. They state that the thermal efficiency is higher, but this is offset by the high cost of preparing the fuel and the high maintenance charges on the plant. I do not suggest that this is a representative case, but it shows that there is another side to the question. The adoption of pulverized fuel by the Detroit Edison Company is mentioned in the paper. In this connection I would

refer members to what the chief of the Research Department of the Detroit Edison Company said in a recent paper which was published in *Power*.*

Mr. C. P. Henzell : I am not prepared to quarrel with the efficiencies given in the paper, but the chief point to a station engineer is the question of cost. Efficiency is to be sought for, but the important figure is the cost per unit. I have seen no figures that one could compare in the same way as the efficiency figures. It is stated that one advantage of pulverized fuel is that heavy overloads can be obtained from the boilers. That is all very well at Lakeside or some of the modern plants equipped with evaporators, but in the majority of stations I do not think that that could be done for long periods without causing trouble. The cost of pulverizing seems to vary. Some authorities give it as 3s. per ton, including power, maintenance, etc. Although chain-grate stokers have certain limitations, I do not think that enough attention is given to preparing or selecting the fuel for them. If crushers are installed in order to reduce large coal down to the most suitable size, and suitable sprayers employed for wetting the very fine coals, much better efficiencies would be obtained. With a washed slack, which is, in a way, a prepared coal, excellent results can be obtained on a chain-grate stoker. The figures given for maintenance costs at Lakeside are very good indeed, but it is possible that, after two or three years and with not quite so much skilled attention, these figures might rise. The author mentions the difficulty of obtaining data relative to the maintenance of mechanical stokers. With chain-grate stokers the maintenance cost is approximately 2d. per ton of coal burned. This figure applies to stokers that have been operating for two or three years.

Mr. F. Dransfield : I do not think that the author has been quite fair in comparing Dalmarnock with Lakeside. The exit temperature at Dalmarnock is in the neighbourhood of 400° F., while that at Lakeside is 200° F., which is remarkably low. On a rough calculation the difference means a 5 per cent difference in efficiency. That difference should be credited to the boiler design and not to the pulverized fuel. It therefore brings the Lakeside efficiency down to 81 per cent, which compares reasonably well with the efficiency of a good chain-grate stoker. The author says that the furnace temperature is greater than with stokers. I have taken a great number of tests on furnace temperatures, and I find that the average is in the neighbourhood of 2 500° F. The author gives a figure of 2 000° F. Firebricks of the best grade melt at approximately 3 000° F. If the temperature is increased from 2 500° F. up to, say, 2 800° F. there is a great danger of the firebricks running. This running is accentuated by the fact that some ashes have a tendency to flux the bricks. How does the author propose to get rid of the 20 per cent of ash deposit in the boilers? It is rather unfortunate that the higher the quality of the firebrick the softer it gets. A really high quality of firebrick crumbles in the hands, and there is therefore likely to be a great deal of wastage in the pulverized fuel due to the erosion of the ash, since a great deal of it is blown through the boiler. With regard to water, the author says that a steel economizer cannot be used owing to the corrosive action of the flue gases. I have been studying the water question for two years and my opinion is that the corrosion is mainly due to the dissolved gases in the water. There is, in addition, a little danger from flue gases.

Mr. W. A. Wordley : Representing, as I do, more the industrial works with their smaller plant than the central stations, I am more concerned with the possibilities of pulverized fuel on plants consisting of, say, 2 or 3 Stirling boilers each of 25 000 to 30 000 lb. per hour normal capacity, and with ranges of from 4 to 10 Lancashire boilers each 8 ft. 6 in. × 30 ft., and evaporating 9 000 to 10 000 lb. per hour. The Stirling boilers can no doubt be converted from mechanical firing to pulverized-coal firing and prove very efficient, but is the cost of conversion and running of these smaller plants justified by the increased efficiency? In other words, does the interest on capital invested justify the expenditure? In considering the Lancashire boiler plants one has to decide which type of combustion chamber best meets the requirements, the external (or Dutch oven) or the internal or firebrick-lining type. Personally, I do not think that either type can prove a great success. The former introduces new sources of heat loss and the latter is not, according to the basis of 1 cubic foot per lb. of coal per hour, of sufficient capacity to ensure complete and perfect combustion. With regard to the cost of installing pulverized-fuel equipments on plants such as I have already mentioned, I have come to the conclusion that it is not a commercial proposition. Certain savings in fuel, labour, etc., would probably be effected, but when one compares these credits with the debits represented by running costs, interest, depreciation, etc., one is forced to conclude that good mechanical-stoker firing still holds the field in industrial works' plants.

Mr. L. E. Hendry : How does the author arrive at a really reliable heat balance? It is very unlikely that the same calorific value can be obtained at each test. After sampling coal most carefully in the orthodox manner, and taking two separate samples, I have found as much as 10 per cent difference in the calorific value. These tests were most carefully taken in a properly equipped chemical laboratory and not in one usually attached to an ordinary plant. As regards mechanical stokers on the Babcock and Stirling boilers and induced draught, I have on 8- and 10-hour tests got up to 86 per cent, and on the whole plant on varying types of boilers, induced draught, some of the boilers with economizers and some without economizers, an average efficiency of 76·6 per cent over the whole year, with about 35 per cent load factor, including all losses. The author does not state what system of draught is used on the Lopulco system. I should be glad if he would say how all the foreign matter (bricks, clay, etc.) in coal which is delivered at power stations is got rid of.

Major H. Bell : Many of the speakers in the London discussion seemed to take exception to the attitude taken up by the author, and suggested that he was championing American practice. I, personally, agree with the author in saying that anything which can contribute to our knowledge of the better combustion of

* Vol. 58, No. 5.

fuel is something that must of necessity be to our advantage, no matter in what form it is put before us. Looking generally at the question of powdered fuel, one realizes that the problems in connection with it can be properly divided into two distinct parts, preparation and combustion. Dealing with the latter first, it seems to me that there cannot be very much doubt as to whether it is not better accurately to prepare a fuel so that by the time it is introduced into the furnace it is in a form in which it can be controlled with a very much greater degree of refinement than can ever be the case with solid fuels of such varying ranges of quality and size as we have been subjected to during the last four or five years. From that point of view I feel that the author is no prophet, and that before very long powdered fuel will be a very serious competitor of the mechanical stoker. In 1919, before the operations of that particular Corporation with whose process the author is so familiar, comparatively little had been done, and the tremendous progress which he outlines has all been achieved within the past four years. The designers of the Milwaukee plant, after going all over the Continent with the object of ascertaining which is the most effective and economic way of consuming coal, decided upon the powdered-fuel process. This installation has been followed by a large number of other plants, the most notable possibly being the Ford plant in Detroit, followed by the same firm's Canadian plant at Walkersville, and others too numerous to mention. The process in connection with cement and steel-works is well known, but I should like to know which particular process is the correct one for steam raising. There is undoubtedly a great diversity of opinion about the various components which have to be introduced into a successful pulverized fuel; for instance, as to whether drying should be introduced or not. This seems to turn upon the amount of moisture which has to be dealt with. It is clear, as the author shows, that there are a number of very large plants which have been operating for a considerable time, in most of which drying is a feature. It is equally true to say that there are a number of smaller plants which have been working for years without any drying, and, of course, at first sight it would seem that if one can eliminate this comparatively troublesome component of the scheme something very material has been accomplished in the way of improving the chances of powdered fuel. One of the greatest of the arguments that have been raised against powdered fuel is dust. I am one of those who subscribe to the opinion that we shall be rather troubled in this country in that connection, and I was impressed by the great height of all the American stacks given in the paper. The reason for this is undoubtedly to overcome the very real troubles which we in this country are beginning to experience. At the present time, by reason of both grits and dust, I cannot help thinking that to install powdered fuel with boilers of any magnitude and with the 100 ft. stacks so familiar in Britain would be to court trouble. In conclusion, I should like to ask the author as a specialist just two questions: (1) In his opinion, is it necessary, in all cases, to use driers? (2) To what degree of fineness is it desirable to prepare powdered fuel? Upon the answers to those questions depends very largely the cost of preparing powdered fuel.

[**Mr. E. H. Hutchinson** also took part in the discussion at Leeds. The substance of his remarks was practically the same as in the discussion at Manchester (see page 445)].

Author's Reply to the Discussion.

Mr. D. Brownlie (*in reply*): In the first place I should like to state that it is hopeless for me to attempt to reply in detail to all the points raised. Not only are there 68 speakers, excluding the discussions at Bristol, Sheffield and Dublin of which reports are not available, but many of the contributions are of great length and I estimate that at least 60 different points have been raised. However, I have done the best that I can in the space available—much in excess of that usually allowed—to answer the more important questions, but to deal fully with every point would more than double the length of my reply.

In the first place I would point out that not one single performance figure has been given me by the Lopulco people. The data are primarily those of Mr. John Anderson of Milwaukee and Mr. R. B. Mitchell of Glasgow, together with those of Mr. Henry Kreisinger and Mr. C. W. E. Clarke, who surely may be regarded as independent. I have omitted a description of the unit system because it is not yet available for large power-station boilers and so far does not seem to be a proved success for steam generation, whilst, above all, to my knowledge no detailed continuous-performance figures are available. If such figures exist, then the obvious thing for the advocates of the unit pulverizer to do is not to criticize my paper but to submit a paper on the unit pulverizer, giving the facts and figures, which everyone would welcome. The same remark applies to other "central" systems, which have apparently not had so extensive an experience of steam-generation work as the "Lopulco." Also, I have not advocated the use of pulverized-fuel firing, but have simply presented the facts in what I have tried to make a readable yet condensed form, so that British engineers may consider this question seriously. Obviously, pulverized-fuel firing has objections, like everything else.

The Comparison between Lakeside and Dalmarnock.

Many speakers are very emphatic, from many points of view, that the comparison between Lakeside and Dalmarnock is not fair. In fact every possible reason seems to have been adduced to explain the elementary fact that Lakeside is running all the year round at 85–86 per cent efficiency and Dalmarnock at 76 per cent efficiency, except the true and obvious one, that pulverized-fuel firing is superior to mechanical stoking. In making the comparison I took one of the largest, most modern, and best-equipped stations in Great Britain, and certainly one which from the steam-generation point of view is not

only controlled on the most scientific lines, probably equalled in this respect by no other in Europe, but is broad-minded enough to allow the results to be published (in this connection also see the remarks of Mr. Blaikie on page 424). Further, as explained at length in the paper the comparison is probably as fair as can ever be obtained, the only real difference being the load factor, for which allowance has been made, and obviously we can never find two stations in the world absolutely identical.

Dealing with several of the points raised, as regards the difference in the quality of the coal, Lakeside is 11 488–12 321 B.Th.U. and 2·25–5·61 per cent moisture, whilst Dalmarnock is 9 802–10 130 B.Th.U. and 12·9–14·8 per cent moisture. Mr. Wimshurst is not correct in taking (page 452) 12 000–13 000 B.Th.U. as against 9 900 B.Th.U., nor is Mr. Pochobradsky in assuming (page 419) as a comparison 3·5 per cent and 14·8 per cent moisture respectively, whilst an equal CO_2 means very little in the sense which he mentions, because other factors are the CO and unburnt gases and the radiant-heat emission. Different moisture-content in fuel is not allowed for in the calculations according to any existing boiler-test code, and this argument can be used both ways in comparing two methods of firing in general. Any difference in heating surface, as raised by Mr. Wimshurst (page 452), is simply that of standard American and British practice, and pulverized fuel in America gives better results than mechanical stoking when both are under the most favourable conditions. Thus at Colfax 1 kW is being obtained for 19 000 B.Th.U. with stokers, and for pulverized fuel the guarantee is 16 000 B.Th.U.

Another complaint, brought forward particularly by Mr. Pochobradsky (page 419) and Mr. Dransfield (page 459) is that the exit flue-gas temperature at Lakeside is only 205° F. against 414° F. at Dalmarnock. The obvious reason is that pulverized fuel is a more efficient method of combustion, the furnace temperature being higher, so that the transmission to the boiler is more effective. It is not the "boiler design" but the method of firing, and it is mainly for the same reason, in answer to Mr. Eccles (page 444), that the chimney-gas temperature at Lakeside is much lower than that at Dalmarnock.

Finally, Mr. Pochobradsky, taking 83·56 per cent efficiency for a day trial at Dalmarnock of 3 hours only, which is of no comparative value on this account alone, and 87 per cent for Lakeside, in spite of the fact that the day figures at Lakeside are 87–91 per cent, coupled with the debiting of Lakeside with calculated figures because the combustion is so efficient that the exit flue-gas temperature is reduced to a minimum, and other equally irrelevant deductions, apparently arrives at the conclusion that Lakeside running all the year round at 85–86 per cent is really inferior to Dalmarnock at 75 per cent. One can hardly be expected to take criticism of this nature seriously. Obviously, the only fair comparison is the actual monthly figures, or at any rate a long series of day trials under equal conditions, especially as regards duration, whilst Mr. Pochobradsky is equally confused over the question of the running and auxiliary costs.

The general idea of most of the speakers in this connection seems to be, although they do not in all cases say so directly, that if the Lakeside plant, exactly as it stands and is controlled, were deprived of the pulverized-fuel equipment and fitted with mechanical stokers instead, then 85–86 per cent efficiency would continue to be obtained and the efficient results are not due to pulverized fuel at all. Mr. Eccles, however, not only states this outright (page 444), but even goes further, as follows: "If Lakeside had been fitted with the Dalmarnock stokers and burning Dalmarnock coal a higher efficiency would have been obtained than was actually done with the pulverized fuel used." He then actually goes on to state that Lakeside requires 100 b.h.p. extra power, although it is clearly shown in the paper that the total auxiliary power, apart from drying, is less than at Dalmarnock.

Finally, as distinct from vague statements without any explanation that the comparison between the two stations is not of any value, such as for example those of Mr. Jockel (page 427) and Dr. Lulofs (page 455), some speakers, such as Mr. Holkunls (page 433), give it as their considered opinion that no useful comparison at all can ever be made between American and European stations!

Naturally, of course, all this trouble would not have arisen if mechanical stoking had been proved to be superior to pulverized fuel, and we should also have been spared such remarkable statements advanced against the use of pulverized fuel as that the moisture of the air of the United States is different from that of Great Britain, the Vitry plant is only to run 900 hours a year, American coals are quite different from British, and there is no useful object in comparing the performance of two electricity stations on different sides of the Atlantic.

Of course, if the Dalmarnock coal were transported to Lakeside and burnt in the pulverized condition there would be no difference at all in efficiency, and most of the speakers mentioned have forgotten that the most efficient and specially designed mechanical-stoker stations in the world do not at present give 80 per cent on continuous performance. To assume, therefore, that mechanical stokers installed at Lakeside would suddenly give 85–86 per cent efficiency is absurd.

Difficulties due to the Lack of a Proper Boiler-test Code.

The increasing confusion and general difficulties due to the lack of a proper international boiler-test code are emphasized very strongly by the discussion, and the remarks of Mr. Baker (page 423) and of Mr. Hendry (page 459) are much to the point. Various speakers such as Mr. Pochobradsky (page 419) have, owing to the present unsatisfactory state of affairs, confused the issue between Lakeside and Dalmarnock, and now that 84–89 per cent boiler efficiencies are being obtained it is becoming imperative that this matter of a boiler-test code be cleared up.

Difference between British and American Fuel.

A number of speakers have stated, or inferred, that there is such a difference between American and British coals that it does not follow that we should obtain equally efficient results with pulverized fuel in Great Britain as are at present being shown in America.

Mr. Partridge (page 419), for example, is much worried that the average calorific value of American coals on the tests shown was over 12 000 B.Th.U. and that engineers in the London area "have hundreds of different classes of fuels at their disposal." I must confess that I cannot grasp this point, since, in answer also to Mr. Hamilton (page 431), for the first time pulverized fuel has given us a method of burning at high efficiency any fuel, irrespective of its heating value, moisture, volatile matter, resinous content, coking properties, mechanical condition, ash, and melting point of the ash.

Further, Sir James Kemnal (page 418) states that American coals are as a rule much more friable than European coals as is shown by the fact that in England we cannot use a mechanical stoker more than 9 ft. wide, whereas in America stokers 24 ft. wide are used. Incidentally, stokers 11 ft. wide are now in operation in Great Britain and units 16 ft. wide are under construction, also installations of over 20 ft. width can be built at any time and are at present being quoted. Further, the friability of coal has nothing to do with the width of stokers, another direction in which British engineering has hitherto lagged behind American. The reason is that we have only just begun to use the modern suspended arch and it is not possible with the out-of-date sprung arch to exceed about 9 ft.

Variety of Fuels that can be Used.

In view of this perfectly well-known and remarkable flexibility of pulverized fuel as regards the quality of the fuel, it is ludicrous that a number of speakers should attempt to show that mechanical stoking is superior in this respect.

Sir James Kemnal (page 418), for example, is emphatic on this point, and Mr. McLaren (page 436) not only says mechanical stoking will burn a wider range of fuels than the Lopulco system, but makes the still more amazing statement that "any amount of ash" in a fuel makes no difference to mechanical stoking. Apart from the fact that even in the discussion itself Mr. Jackson (page 448) gives an example of his own experience of burning successfully in a well-known Newcastle station a quality of fuel by pulverizing methods which is quite impossible with chain-grate stokers, statements of this character will enable the experienced power-station engineer to draw his own conclusions as to the calibre of some of the arguments advanced against pulverized fuel.

Capital Cost.

Another alleged objection to pulverized fuel on the Lopulco system is the capital cost of the installation as compared with the unit pulverizer and mechanical stoking, and some extraordinary statements have been made in this connection.

Sir James Kemnal (page 418) first of all says "no mention is made in the paper" of this vital matter of capital cost; whereas the matter is discussed on pages 415 and 416. He then goes on to assume that "the cost is very high, probably five or six times as much as that of mechanical stokers of the best kind."

Mr. Pochobradsky states (page 421) that the cost of a pulverized-fuel plant to deal with 50 tons a day is £11 562, taken from the paper (page 391), the period being that of the abnormal high prices of 1918, whilst a unit pulverizer for the same duty would cost £800. Mr. Hollands (page 433) says that "the difference in cost is enormous," and the same point is raised by Mr. Forrest (page 454).

It will be agreed that the engineers and managerial staffs who control, for example, the Detroit Edison Co., the Ford Motor Co., the Cleveland Electricity Co., the Cahokia station at St. Louis, the Colfax installation at Pittsburg, the Union d'Électricité in France, and the Willesden and St. Pancras stations in Great Britain know what they are doing, which would not be the case if a number of the arguments advanced on this point are worth anything. That is to say, we should have to admit that many of the most prominent industrial concerns of the world who have placed orders for pulverized-fuel plant to the extent of a consumption of nearly 4 million tons of coal per annum incurred huge and unnecessary capital costs.

It is very difficult, in fact almost impossible, to give a real comparison in capital cost between modern pulverized fuel and mechanical stoking, because so much depends on the conditions. The unit pulverizer is hardly worth considering on present knowledge, as it is not applicable to large boilers and sustained high efficiency, apart also from the fact that it requires, like any other method, auxiliaries in the way of coal-crushers, conveyers and overhead bunkers, together with ash conveyers.

Taking, however, first of all the case of entirely new plant, we have to consider two factors, the size of the plant and the increased output due to pulverized fuel. On one large boiler only, say 50 000–100 000 lb. per hour, the comparative capital cost of the equipment was in a recent instance approximately $1 \cdot 5 : 1 \cdot 0$ (pulverized coal of course being dearer), taking everything on the latest lines—economizers, superheaters, air heaters, fans, overhead coal-bunkers, ash-handling plant, chimney, and the correct combustion chamber in each case. This, however, is not a fair comparison because the output of the pulverized-fuel plant is much greater. Thus at Willesden a 50 000 lb. boiler with 62 500 lb. peak load on mechanical stokers will give 60 000 lb. normal load, 72 000 lb. continuous overload, and 80 000 lb. peak load with pulverized fuel, and when the basis of equal steam output is taken there is little difference in capital cost. For a large plant of, say, six 50 000 lb. boilers, pulverized fuel is no more expensive or even cheaper, as is well known from the extensive American experience, and all the remarks about greatly increased capital outlay can be disregarded. As applied to existing mechanical-stoker plant the matter is different, and in many cases the opinion of Mr. Pearce (page 442), that in these circumstances the capital cost will outweigh the savings, is correct, chiefly because the boilers have to be reset to obtain a proper combustion-chamber volume.

High Efficiency with Mechanical Stoking.

In reply to Mr. Rowe (page 435) and also in connection with the remarks of Mr. Cauthery (page 453) and Mr. Partridge (page 419), very high efficiencies for short tests have certainly been obtained with mechanical stoking, and I am aware that 88 per cent is claimed with

marine boilers and forced-draught, air-heater equipment, and also 85–89 per cent with ordinary water-tube boiler installations of stokers, superheaters, economizers and air heaters. Apart from the great confusion that exists in the method of calculating and expressing boiler-plant tests, the point is, however, that these figures only apply to short tests and not to continuous running.

The Difference between Continuous Running and Test Conditions.

In connection with this question of high efficiency obtained by mechanical stokers the discussion shows that it is almost impossible to get many engineers to understand the difference between a short test of a few hours under special conditions and the actual running results from month to month. The Lopulco figures at Lakeside, 85–86 per cent efficiency, are based on the water evaporated and the coal burnt each month, including all light load, starting-up and shutting-down losses, whereas the short tests vary from 87 to 91 per cent efficiency. In spite of very high figures on short tests, the most efficient stoker plants in the world are only giving about 75–78 per cent efficiency, as, for example, in the case of Colfax and Dalmarnock.

Mr. Hendry (page 459) gives an excellent illustration of this, a typical mechanical-stoker plant running at 76·6 per cent efficiency all the year round but on which as high as 86 per cent has been obtained on a 10-hour test. Yet many speakers persist in claiming 80–85 per cent short-test efficiency for mechanical stokers against the 85–86 per cent continuous figures for Lakeside and not the test figures of 87–90 per cent. For example, Mr. D. Wilson (page 421) assumes that my figure of 75 per cent for the performance of mechanical stoking is a misprint and speaks about 80 per cent and over as if this applied to continous performance. It was for this reason, in trying to emphasize the importance of month-to-month figures, that I mentioned the 400 tests. Again, Mr. Townley (page 458) takes 81·5 per cent as the performance of his mechanical-stoker plant, admits that this is only for 10-hour test figures, and then proceeds to compare this with the continuous figures of 85–86 per cent efficiency at Lakeside. His assumption of only 4 per cent saving is of course quite wrong and should be 6–9½ per cent in comparison with Lakeside day tests of 87–91 per cent.

Steam-generation Efficiency and Cost of Power Production.

Quite a number of speakers also have assumed that I have devoted nearly all my attention to the increase of steam-generation efficiency and said nothing about the total cost of the production of power, which it is insinuated in some cases is really higher with pulverized fuel. Thus Sir James Kemnal (page 418) says that steam-generation efficiency, whether 80 or 85 per cent, does not matter so long as the total cost per unit generated is less, whilst Mr. Partridge (page 419) is of the opinion that we ought to include such items as labour, repairs and maintenance, and interest on capital.

Mr. Wilmshurst says (page 452) that he would prefer to hear less of the overall efficiency of the boiler and more of the total commercial costs of running per unit generated—such figures to include all capital charges and the cost of running auxiliaries.

Again, Mr. Blaikie states (page 424) that "the paper is mainly concerned with the thermal efficiency of steam generation." Mr. Stubbs (page 447) says that "the really important features are lost sight of because of his [the author's] anxiety to stress the question of efficiency." Mr. Troup (page 430) thinks that I have not done myself justice by emphasizing thermal efficiency to such an extent. Further, Mr. Petford (page 457) speaks of "straining after higher efficiencies," Mr. Forrest (page 454) suggests that what matters is the lowest cost of steam generation and not efficiency, whilst Mr. Devey in his remarks (page 434) seems to be under the impression that I have dealt only with efficiency.

These speakers do not appear to have read the paper thoroughly. I have not devoted undue attention to efficiency at all, but have dealt in the fullest detail with every one of the advantages and disadvantages of pulverized fuel, and in this section out of a total of 20 pages (396–416) only 8 pages (396–404) deal with efficiency. I stated also in the clearest possible fashion that the most valuable portion of the paper related to the costs of running at Lakeside.

In reply to the platitudes about generation costs, obviously if the net cost of generating steam is reduced, as shown in the paper, then also the overall power costs will be lowered accordingly, and I have not given these latter because the paper deals with steam generation and is already 40 000 words in length. I can only say again, as already stated in the case of capital cost, that those in charge of many of the most prominent firms in the world know what they are doing and would not have adopted pulverized fuel if the net generation costs were thereby increased.

Objections to the Water Screen.

Another common contention in the discussion is that the water screen for the prevention of the slagging is an objection. In the first place it is stated to be dangerous to work. Thus Mr. Cauthery (page 453) thinks that it may give trouble by overheating, contraction and expansion, and we know from Mr. Pearce (page 443) that one water-tube boiler firm are not only strongly opposed to the water screen but actually have stated that they did not think a boiler insurance company would insure a boiler with such an attachment. Again, it is supposed to require abnormally pure water. Mr. Allwood (page 453) regards it as a weak point unless particular attention is given to the water, and Mr. Train (page 437) is of the opinion that it "is barred on account of the quality of the feed water" and we ought to concentrate on designing a furnace without water screens. Finally, the water screen is stated to be unnecessary, and a number of speakers such as Mr. Hutchinson (page 444), Mr. Hollands (page 433), Sir James Kemnal (page 418) and Mr. McLaren (page 436) are of the opinion that slagging is or can be eliminated without a water screen and merely by proper furnace design.

The facts are, in answer also to Mr. West (page 430) and Mr. Hamilton (page 431), that the water screen does not give trouble and the installations at Lakeside and

Oneida-street have been running for several years without any difficulty, whilst 60 000 kW at Cahokia has been in operation for 6 months. Also it is a misstatement to say that insurance companies have raised any objection, either in America or France, to the water screen, as must be obvious from the number of plants at work.

The best methods of preventing slagging are a matter of opinion, but the water screen is mainly responsible for the fact that several million tons of coal in the pulverized condition are now being burnt per annum for steam generation. When unit-pulverizer firms or any of the speakers can show us actual results of long running with varying qualities of coal on power stations without a water screen, then we can consider their statements seriously. It may be mentioned also that the chief reason why pulverized fuel makes such slow progress for general furnace work, as in the iron and steel industries, is because unit pulverizers cannot entirely stop slagging, and, as Mr. Clements points out (page 425), any satisfactory system must guarantee to prevent this trouble. Finally, from a theoretical point of view the objections to the water screen have no point at all, and on what grounds Sir James Kemnal (page 418) says that it is "a somewhat crude arrangement" is not clear. The apparatus is a 4 in. steel tube, the same as the tubes of the boiler, and it is less liable to burn out or give trouble, and no more requires specially pure water than the boiler tubes. It would be much more logical to apply the above objections to the bottom two or three rows of tubes of the boiler nearest the furnace which have to do 70 per cent of the whole evaporation, an inherent defect in most water-tube boiler design.

Size of the Combustion Chamber.

Arising out of the comparison between Lakeside and Dalmarnock, several speakers seem to regard the size of the combustion chamber as a disadvantage. The fact is, however, that a large combustion space is essential to efficient combustion, and mechanical-stoker practice is suffering heavily because this fact is not recognized in Great Britain as it is in America. The extra capital cost of a large combustion chamber is wiped out in a month or two by the extra efficiency. In this connection the point raised by Mr. Hutchinson (page 444) that the large combustion chamber cannot tend to efficiency obviously has no value since it is at present giving the highest boiler-plant efficiency in the world, whether on continuous running or short tests. Some speakers such as Mr. Nicholls (page 453) complain that a part of the high efficiency of Lakeside is due to proper dimensions in this connection, which is quite correct, but in making the comparison I cannot help it, and all along I have given mechanical stoking the advantage in case of doubt (see page 400).

Mr. Rutland (page 452) seems to regard with pride the fact that marine boilers are crowded into a small space. This is one of the chief reasons why the efficiency of marine steam-generation is so low, averaging probably less than 55 per cent, whereas pulverized fuel in a large water-tube boiler with sufficient combustion-chamber space will give 86 per cent, that is, about 36 per cent reduction in the coal bill. An interesting example from marine practice is given by Mr. W. J. Muller, the chief engineer of the Dutch steamship company, the Koninklyke Paketvaart Maatschappij of Amsterdam, in a paper read in 1923 before the Institution of Naval Architects. He shows that a marine water-tube boiler with mechanical stoking gave 65 per cent efficiency with the usual combustion space, but by merely raising the boiler 2 ft. the efficiency went up to 75 per cent, that is a saving of over 13 per cent in the coal bill. In spite, however, of the triumphant competition of the Diesel engine, marine steam-generation practice continues to blunder along in the same inefficient manner, of which small combustion space is only one of many illustrations.

In reply to Mr. Blaikie (page 424), the main reasons why a Lancashire boiler plant will give 82·5 per cent efficiency with cramped combustion space is the use of a high-grade fuel of low ash-content, often with a low volatile content, adequate draught, tight settings, good firing and an extensive equipment of superheaters and, particularly, economizers.

Fine Ash Discharged from the Chimneys.

Very many of the speakers have raised the point—on purely theoretical grounds—that one of the most serious objections to the Lopulco system of pulverized-fuel firing is a huge amount of fine ash discharged from the chimney. It has been stated also, apart from the present discussion, that 70–80 per cent of the ash is discharged from the chimney, oblivious of the other objections that about 50 per cent of the ash is deposited in the furnace and would cause slagging in the absence of the water screen, whilst 25–30 per cent causes trouble in the boiler tubes and flues. Thus, as an example, Mr. Partridge says (page 419) that "every engineer whom we consulted" told him this and he is of the opinion that "the London area is a very different proposition" from a station by a lake, especially because of "the stringent rules and regulations of the County Council."

Whilst Mr. Petford (page 457) talks about the medical authorities not looking on pulverized fuel with favour, Mr. Mallinson (page 440) is nervous about the deleterious effect on the air of Manchester, and Dr. Lessing states (page 421) that if only 12 per cent of the ash escapes from the chimney this would mean that our vanishing smoke problem would be replaced by a dust problem and that for a successful solution of the powdered-fuel problem the ash must be eliminated. Also Mr. Moxon (page 434) and Mr. Rutland (page 452) express unfavourable opinions upon pulverized fuel on this account, whilst Prof. Bulleid (page 454) wants to know if there is any danger of the ash choking up rain-water spouting, and Alderman Walker (page 447) has apparently misunderstood the figures given in the paper and on the lantern slides.

The facts are, as already stated, that the ash discharged at Lakeside is $17\frac{1}{2}$–25 per cent of the total ash, about 3 per cent of the coal fired, which is approximately the same as that discharged from chimneys to-day with mechanical stoking except that in the latter case much nuisance is caused because of the large particles. The best information on the ash question is contained in a recent paper by Mr. H. D. Savage before the American

Society of Mechanical Engineers. There are only two places in the world, Lakeside and Oneida-street, where the exact amount of the ash discharged has ever been determined, and the ideas often expressed that 40–80 per cent of the ash is discharged are mere guesswork. There has, in practice, never been any trouble with ash, either at Lakeside, as pointed out by Mr. Evans (page 422), or anywhere else. Mr. Savage also mentions that with a super-station of 10 boilers of 15 000 sq. ft. heating surface burning 1 176 tons of coal per day, at 10 per cent ash this is 117·6 tons of ash per day. Even if 30 per cent were discharged from the chimney, that is 35 tons of ash per 24 hours, and if this came down within a radius of 1½ miles, that is 7 square miles, obviously impossible, the ash deposit would be 0·00031 lb. per square foot per 24 hours, or 1·8 ounces per annum. The particles are so extraordinarily small, being the ash skeleton of pure mineral matter from coal of which 65 per cent passes through a 200 mesh, that they are comparable in size, as Mr. W. Wilson (page 456) expresses it, with the motes floating in every sunbeam. In practice they remain suspended in the air until washed down by the rain.

The Height of the Chimney required for Pulverized Fuel.

A number of speakers have assumed that because the Ford steel chimneys are 327 ft. high therefore one of the objections to pulverized fuel is that an enormous and costly chimney is necessary. Thus, for example, Mr. Wadeson (page 458) says that the height of the chimney in the pulverized-fuel station is about 2¾ times that of a mechanical-stoker station, and Mr. Hutchinson (page 444) also mentions this point. They seem to have forgotten that the Ford chimneys deal normally with 70 per cent blast-furnace gas and 30 per cent pulverized coal, so that they might as well have pursued this argument to the end and claimed that pulverized coal emits so much dust from the chimney that even for only 30 per cent of pulverized-fuel chimneys over 300 ft. high are essential. The reason for the great height is that the Ford Company prefer natural draught to mechanical draught, and the above statements are obviously of no value because the Lakeside chimney is 220 ft. high and a very large number of mechanically-fired plants in Great Britain have chimneys as high as this. The lowest practical height for a chimney is a matter of opinion, as we find in connection with the general propositions of high chimney versus medium-height chimney and mechanical draught. Also, as Major Bell points out (page 460), the 100 ft. chimney is already giving much trouble with mechanical stoking.

The Lopulco Vertical Drier.

Mr. McLaren (page 436) says that this "apparently has not yet been thoroughly tried." The answer is that it has been running experimentally for 2 years past at Oneida-street and has also been in operation at the Cahokia plant, St. Louis (60 000 kW), for 6 months.

The Degree of Drying Necessary for the Coal.

With regard to the statement made by Mr. Hollands page 433), it is quite true that I said in the *Iron and Coal Trades Review* drying down to 1 per cent moisture in large revolving driers is a formidable operation, an opinion which I still hold, although we have always got to look at the final net results. But to-day it is not necessary to dry down to 1 per cent or use complicated driers as explained in the paper (for example, page 395), and in reply particularly to Mr. Malpas (page 434), it is now found necessary for the most efficient results in the pulverizer only to drive off the free or surface moisture. The efficiency of the pulverizer is not affected by what is vaguely termed the hygroscopic moisture which is a part of the coal substance. The new vertical Lopulco gravity drier, as described in the paper, is a small and compact apparatus with no moving parts, occupying little room and requiring practically no attention, circulating a mixture of air and exit flue gases at 215° F., which absorbs 3 kW per ton of coal dried. Further, in reply to Mr. Malpas (page 434) the temperature is regulated by means of a damper by altering the amount of cold air supplied. Nearly all the objections raised to drying the coal, such as those of Mr. Hollands (page 433), have no point in reference to this improved type of drier.

Unburnt Ash in Coal.

Just as many power station engineers imagine their boiler plant is running at 75–80 per cent efficiency all the year round, remarkable ideas still exist as to the loss by unburnt fuel in the ash. As an example of this Mr. D. Wilson (page 421) states that "in a well-operated station the carbon in the ash does not exceed 10 per cent" and that "there should be no difficulty in keeping the loss down to 0·5 per cent," meaning presumably by this the figure for the actual coal loss, and then goes on to say that my figures of 3–5 per cent for mechanical stoking are "inaccurate and liable to mislead." The true state of affairs is, however, illustrated by a number of speakers in the discussion. Mr. Maxted (page 432) gives the details of a boiler plant of 6 Babcock and Wilcox boilers under his control fitted with chain-grate stokers and operated on the most scientific lines at 75 per cent boiler-plant efficiency. There is on the plant a loss in the ash and clinker of 5 per cent of the coal fired, that is 1 300 tons of coal per annum, whilst Dr. Lulofs (page 455) of the Amsterdam electricity station gives it as his opinion that 5 per cent of coal lost as unburnt fuel in the ash is a low figure.

Mr. Jackson (page 449) confirms in his experience 1–2 per cent coal loss in the ash, whilst the riddlings on chain-grate stokers are 35 per cent, and Mr. Evans (page 422) gives another example of 20 per cent. The estimate of 3–5 per cent in the paper is an understatement.

Large Size of Boiler with Pulverized Fuel.

In this connection, confirming the remarks made by Mr. Evans (page 422), Mr. Swindin (page 428), Mr. Troup (page 430) and Mr. Platt (page 454), modern pulverized-fuel firing has rendered possible the huge boiler which cannot be operated with mechanical stokers or unit pulverizers. I am glad that Mr. Erith reminds me (page 426) that the largest mechanically-fired boiler has about 170 000 lb. evaporation per hour, but pulverized fuel has been the sole means of making possible the unit

of 30 000 sq. ft. heating surface or over, with a normal evaporation of 300 000 lb. and an overload of 400 000 lb. per hour. It is now proposed, because of the perfection of pulverized fuel, to construct 40 000 sq. ft. heating-surface boilers so that one unit only will supply a 35 000 kW turbine, thus simplifying power-station design.

Temperature in Combustion Chamber.

Several speakers such as Mr. Hutchinson (page 444) and Mr. Dransfield (page 459) have quite misread the temperature of 2 100° F. mentioned on page 405 of the paper in connection with the Ford plant. This relates to 70 per cent blast-furnace gas and 30 per cent pulverized fuel, and not to pulverized fuel only, the temperature of which is certainly well over 2 500° F.

Vibrations of the Boiler.

Mr. Rutland (page 452) raises the interesting point of "organ pipe effects," which is a peculiar vibration of the whole boiler due to pulsations in the combustion chamber. I have not heard of any case of this actually happening with pulverized coal, although presumably it might take place. The cause is rather mysterious and I have known several very troublesome and almost alarming cases of this with chain-grate stokers, in one of which a change in the quality of the coal caused an instant cessation of the effect. The same result can be given to a lesser degree in Lancashire boilers if the superheater is not provided with a mid-feather.

Troubles due to Liquid Condition of Pulverized Fuel.

Mr. Phillips (page 452) raises the very interesting point of the pulverized fuel becoming "liquid," due to particularly good drying and grinding, and running right through the feeders like water. Mr. Phillips is quite correct that the variable pitch of the cast-iron screw feeder described in the paper is designed to reduce this trouble to a minimum. This variable pitch tightens up the coal at the end of the feeder, giving a "plug" of coal, which has the double function of preventing the 10 per cent air at 12 in. water gauge, added at the discharge, from passing back into the pulverized-coal bunker and also acting as a barrier in the case of the "liquid" condition mentioned.

Wear and Tear on Burners.

Mr. Rutland (page 452) asks if there is any mechanical wear and tear on the burner tips with pulverized fuel, following upon his experiences in this respect with unfiltered oil in oil burners. There is no trouble in this respect and the two cases are not parallel, since there is ample clearance space through the burners and the pulverized fuel-air mixture behaves practically as a gas. A more suitable comparison would be with the gas-firing of boilers and not oil burners with an excessively small aperture.

Combined Mechanical Stoker and Pulverized-fuel Firing.

Dr. Lulofs (page 455) deals with a new development which he has undertaken at Amsterdam electricity station, that is the combination of a unit pulverizer and a chain-grate mechanical stoker. The idea briefly is to install a unit pulverizer using much less than the normal amount of air at the back end of the stoker, the jets being parallel with the chain grate and at a slight angle inwards. In this way the obvious and perfectly well-known defect of chain-grate stokers, the admission of excess air at the back as the fires burn thin, giving about 5 per cent CO_2, is remedied by using this air to complete the combustion of the pulverized coal. This is stated to have given excellent results, at least 20 per cent increase in evaporation, and the method is certainly interesting in spite of the defects of the unit pulverizer (to be discussed later).

Radiation Loss.

In reply to Mr. Blaikie (page 424) the radiation loss from a pulverized-fuel plant is not excessive in spite of the large combustion chamber, and the figures for Lakeside of $1\frac{1}{2}$ per cent and of $2\frac{1}{2}$ per cent for Dalmarnock are probably both on the generous side. The old ideas of 5 per cent radiation loss in the case of a boiler plant are quite erroneous.

Cast-iron versus Steel-tube Economizers.

I can assure Sir James Kemnal, in reply to his remarks on page 418, that I am quite aware that in a number of cases cast-iron economizers have been replaced by steel. I am, however, also acquainted with the fact that in various instances the steel-tube economizer has proved to be most unsatisfactory. In this connection the statements made by Mr. Rushworth (page 453) are somewhat significant, not only as regards failures of steel-tube economizers, but also because cast-iron coverings are now being adopted to try to protect the steel.

In reply to Mr. Jockel (page 427) the trouble with the steel-tube economizer is both external and internal corrosion, as pointed out also by Mr. Dransfield (page 459).

In answer to Mr. McLaren (page 436), I do not think that the steel-tube economizer will outlast the water screen, and the proper comparison for the latter is the lower boiler tubes and not the economizer tubes.

Marine and Cylindrical Boiler Practice.

In reply to Mr. Hall (page 434) and Mr. Rutland (page 452), so far as I know, pulverized-fuel firing has made no headway at all with marine boilers, or in fact with any type of cylindrical boiler, a matter obviously of the greatest importance since by far the greater amount of coal burnt in Great Britain for steam generation is consumed in Lancashire boilers. This also is in answer to Prof. Bulleid (page 453) and Mr. Wordley (page 459).

The Unit Pulverizer.

Most attention of all has been given in the discussion to the question of the so-called unit pulverizer, and accordingly I will deal with the matter at some length. The reason why I omitted unit pulverizers from the paper has already been explained (pages 385 and 460).

In the first place, it may be stated that the distinction to-day between the so-called "central" system and the

so-called "unit" system of pulverizing no longer holds good, since the latest Lopulco application appears to combine the advantages of both. In the central system it is usually understood that the crushing, drying and pulverizing of the coal are carried out in a separate pulverizer building and the pulverized coal sent to all the different boilers or furnaces in the boiler house, as at Lakeside, whereas in the unit system a single combined pulverizer, separator, and air-supply fan are used in one unit in front of each boiler, in place of the mechanical stoker.

In the modern Lopulco system, of course, as at Vitry, Cahokia, etc., no separate building is required, each boiler having its own independent vertical drier, pulverizer, separator, pulverized-fuel storage bunker, feeder, water screen and hollow brickwork, all of which are worked separately and independently of one another at practically continuous, maximum efficiency, whilst the space occupied is little more than with unit pulverizers or mechanical stokers and ash conveyers. The fact is also that the unit system has had little or no success for large-scale steam generation, and because of this the central system had to be devised so as to eliminate the obvious defects of the former method. To-day in the United States practically all the boiler plants of any importance fired with pulverized fuel do not use the unit system. My paper is concerned with steam boilers only, not furnaces in general, and Mr. Mallinson's statement (page 440) that unit pulverizers are being developed in the United States is really beside the point, just as are Mr. Hutchinson's remarks (page 444) that one system of unit pulverizers burns $1\frac{1}{2}$ million tons of coal per annum. About 30 million tons are burnt every year for all purposes and I can assure Mr. Atkinson (page 422) that I am not in the least surprised to hear that over 400 turbo-pulverizers are installed, but what concerns this paper is steam generation.

Alderman Walker (page 447) states that he finds on inquiry there are quite a number of unit plants at work, but he does not enlighten us any further as to the result of his investigations. However, Mr. Hollands (page 433) states that 160 unit pulverizers of one make are operating on boiler plants, and Mr. Hutchinson says that 60 plants are at work in France, but no details are given.

As we have already had in the discussion a fairly comprehensive account of the advantages of the unit pulverizer from various speakers, including Mr. Maxted (page 432), Mr. Clemitson (page 451) and Mr. Hutchinson (page 444), it will not be without interest to give the objections to the unit pulverizer, which would seem to be on present knowledge as follows :—

(*a*) Since no magnetic separator is used there is always danger from a serious breakdown due to stray metal particles in the coal, such as nails, bolts, cartridge cases, washers, canister lids, and similar material.

(*b*) A minor accident shuts down the whole boiler, whereas this does not happen on the central system in general, with reserves of pulverized coal and a number of separate burners and feeders.

(*c*) The absence of drying, and the assumption (which is not admitted) that any coal up to 12 per cent moisture can be used direct, mean that the coal varies in moisture content and therefore in physical properties. This results in uneven grinding; that is, a 5 per cent moisture coal does not give the same result as a 10 per cent coal, whereas on the central system there is always one moisture content.

(*d*) The presence of moisture in the coal means excessive power required for the pulverizer. Mr. Train (page 436) realizes this point and suggests the addition of a vertical drier to the unit pulverizer.

(*e*) The presence of moisture in the coal means a lower boiler-plant efficiency, since the moisture has to be evaporated into steam in the furnace, which escapes in the exit gases and carries away a large amount of (latent) heat.

(*f*) A unit pulverizer will work only whilst the boiler is in actual operation, and at a corresponding rate, whereas on a central system, such as the Lopulco, 24 hours' coal supply can be pulverized in 16–17 hours irrespective of the boiler output. Consequently, the pulverizing is done largely at night when the station is on light load and the cost of power practically nil.

(*g*) What may be termed the essential defect of the unit pulverizer is that it is not possible to carry out at one and the same time at maximum efficiency in a single machine the entirely different operations of pulverizing coal, separating the particles, conveying, mixing with air, and supplying to the furnace at the various rates of operation which depend upon the fluctuations in the steam demand. Each one of these operations is only working at a maximum efficiency at one speed, and needless to say these speeds do not coincide. At any given rate of burning, therefore, the net efficiency of the pulverizer unit is the average of all the different operations, and this efficiency is nearly always low because the given speed can only be approximately correct for one or two of the different functions. Thus as the steam demand rises to a maximum the efficiency of the grinding falls heavily, the power required rises, the wear and tear increase, and vibration generally results. Again, a very serious point, there is no real control over the air supply and little flexibility, since the speed of the pulverizer, which governs the air, has to be adjusted, depending on the other factors. It was these reasons that caused the central type of system to be devised, in which the pulverizer works continuously on dried coal at one speed only, that of maximum efficiency, since between it and the burners is a large storage bunker. The coal is intimately mixed with air in an entirely separate feeder under easy control, and is burnt in a number of independent burners working only within a range of high efficiency, individual burners being shut down or started up as required for very light or heavy loads. This will answer particularly Mr. Clemitson's remark (page 451) as to why it is necessary to "go to the trouble" of separators, feeders, etc.

(*h*) The power required by the unit pulverizer is extremely high, averaging 2–4 per cent of the output of the boiler, but at high speeds and peak loads the figure may easily be 5 per cent or over, especially when the pulverizer is a little worn. On the Lopulco system with the new vertical drier the total figure is only about 1 per cent. Mr. Carr-Hill (page 425) gives it as his opinion that a unit pulverizer takes about 3 times the power of

a modern pulverizer, viz. 40–50 b.h.p. per ton as against 13–14 b.h.p., based on 70–75 per cent through a 200 mesh. In reply to Mr. Townley (page 458) it is not generally agreed that "pulverizing takes 20–25 kW per ton." As stated in the paper the Lopulco guarantee is 19½ kW; and with regard to Mr. Pochobradsky's remark (page 420) that the power consumption of the unit system is less than what he calls the central system, I take the strongest exception to his statement, without any figures to support it, that the unit pulverizer takes 25 kW per ton.

(*i*) The wear and tear on unit pulverizers is apt to be very severe on continuous running because of the variations in speed necessary, the construction also often giving heavy vibration at top speed. The beaters wear out very quickly, giving still more inferior grinding and increased power consumption.

(*j*) The mixing of the pulverized fuel and the air is not sufficiently intimate to ensure best results and gives "stratification" in the combustion chamber, as mentioned by Mr. Carr-Hill (page 425). That is to say, since the mixing of the air and the coal is imperfect and the grinding very uneven, in the combustion chamber the heavier particles at once fall to the bottom before they have time to be burnt, so that there is almost a series of different strata, the top being composed of the finest particles and the heaviest being at the bottom, the combustion therefore not being complete. Further, these large particles vary in ash content.

(*k*) On long running a unit pulverizer will not work with only 20–25 per cent excess air owing to the defective grinding and mixing.

(*l*) The unit system sooner or later gives trouble due to slagging, depending on the quality of the coal, especially as the size of the plant increases. This trouble is aggravated by the heavy partially-unburnt particles of coal falling to the bottom of the chamber, and eventually reduces considerably the efficiency of the plant.

(*m*) Another result of imperfect combustion is that the ash in the average unit plant is not completely burnt and cannot approach the Lopulco figure of 0·5 per cent unburnt-fuel loss. In one example of unit pulverizers the ash in the bottom of the furnace contained 8 per cent combustible, whereas in the last pass of the boiler the figure was 38 per cent.

(*n*) A unit pulverizer required a considerable amount of labour and attention, with constant skilled supervision of each separate pulverizer, which would be a troublesome matter in the case of a large station.

(*o*) A unit pulverizer cannot be applied to very large boilers.

(*p*) A point of the highest importance is that on the Lopulco system boilers can be operated entirely from a distant panel switchboard, the coal and air being manipulated by means of small levers as at the Ford plant. This has long been an ideal, leading to the highest efficiency, and is impossible both with unit pulverizers and with mechanical stokers.

(*q*) The net result is that a unit pulverizer will not give 85–86 per cent continuous efficiency on a boiler plant, even with small or medium-sized boilers, and, as already stated, no figures to the contrary are available. There are plenty of vague statements. Thus, Mr. Hollands (page 433) says "the unit system is giving results quite as good as those obtained on any other system," whilst Mr. Pochobradsky (page 420) states that "the performance of a unit pulverizer is in every respect equal to that of a central pulverizing plant and the efficiency of firing is exactly the same in the two systems." Mr. Atkinson (page 422) says "we have had a large number of boiler tests made, many of which show a total efficiency of 85 per cent and over," and Alderman Walker (page 447) thinks that I could have got the same information, that is long detailed performance figures of 85–86 per cent boiler-plant efficiency from both users and makers of unit and other systems. Also, Mr. Dennis (page 432) says that the Buell unit pulverizer will give "all the Americans claim to do." Most of these speakers do not give any figures and I suggest the reason is that such data do not exist.

It is very obvious, therefore, that many of the advantages of the unit pulverizer, such as low first cost, convenience, small space and no drying of the coal, are completely offset, although of course the unit pulverizer is very useful for many cases, such as the adaptation of Dr. Lulofs (page 455), but it does not at its present stage of development compete seriously with the Lopulco or other central system on boilers of the largest size at 85–89 per cent continuous efficiency.

General Remarks.

As regards Alderman Walker's observations (page 447), the answers to the points which he raises will be found in the paper.

In answer to Mr. Phillips (page 452), I have no information at all with regard to Hammersmith and we are all waiting for the results. In this connection I should like to know why Mr. Hutchinson did not quote the Hammersmith figures.

Sir James Kemnal (page 418) makes, in addition to those already discussed, a number of general statements that are quite unwarranted. The statistics issued by the Electricity Commissioners do not show the figures relating to steam production, and the number of private firms who keep such figures is very small. I suggest that the amount of apparatus required is much more a defect of mechanical stoking than of pulverized fuel, especially because of the ash and clinker problem. Also I will challenge Sir James Kemnal to quote a single instance where mechanical stoking is giving an increase in boiler output equal to pulverized fuel. Further, with regard to his remark that "the author states also that British power station practice is far behind that in America," this is quite unwarranted. I have said nothing of the kind, and the only reference in the whole of the paper to a comparison between British and American engineers is on page 400, where I state we are behind America in regard to furnace volume, which is quite correct. Several other speakers have raised, without any justification, the point that I have been antagonistic to British engineers.

Finally, I did not mention that the ash varies with the nature of the coal, because this is obvious to everyone.

In reply to Mr. Devey (page 433), I have not suggested the installation of pulverized-fuel plants and I did not

mention the matter in any part of the paper, nor have I proposed that any existing plant should be scrapped. I quite agree that what we require is more scientific control of boiler plant, and I have advocated this continually for over 12 years past.

It is futile for several speakers such as Mr. McLaren (page 436) to emphasize that the Vitry guarantee is "only 84 per cent efficiency" and therefore to cast doubts on the Lakeside figure of 85–86 per cent and on pulverized fuel in general attaining these figures. The obvious answer is that the Lopulco guarantees are in many cases much higher than Lakeside, as, for example, 88¼ per cent at Trenton Channel, and 89 per cent at Willesden, and presumably the Lopulco people conduct their own business, including the extent of the guarantee, to suit themselves.

With regard to Mr. Atkinson's point (page 422) concerning an article of mine in February 1922, we all change our opinions as experience accumulates. It is not very long ago that Mr. Atkinson himself was an enthusiastic advocate of the central system, which he now condemns in favour of the unit system.

It is extremely interesting, as mentioned (page 425) by Mr. Clements, that the Park Gate Iron and Steel Co. should have put in the first pulverized-fuel blast-furnace-gas plant, as I certainly was not aware of this, whilst the Calumet figures given (page 426) by Mr. Duncan are of much value, although of course most British power stations have not yet installed very wide stokers.

In reply to Mr. Jockel (page 427), I have referred to Mr. Harvey's report in various parts of the paper, as on page 391 for example, and with regard to the point raised by Mr. Hamilton (page 431), so far as I know, carborundum bricks have not been tried and do not seem necessary in view of the efficiency of the air-cooled walls.

PROCEEDINGS OF THE INSTITUTION.

711TH ORDINARY MEETING, 14 FEBRUARY, 1924.

(JOINT MEETING WITH THE PHYSICAL SOCIETY OF LONDON.)

Mr. C. C. Paterson, O.B.E., Vice-President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 31st January, 1924, were taken as read and were confirmed and signed.

Messrs. J. W. Fraser and W. H. Nottage were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows:—

ELECTIONS.

Member.

Mather, John.

Associate Members.

Ayengar, Tanjore Krishnasami R., B.A.
Clements, Fred.
Cooper, Harold Cyril, B.A.
Holman, Cecil Leonard.
Inouye, Ikutaro.
Linskill, Harry.
Nicholls, Frank.
O'Connor, Timothy Patrick, B.E.
Orchard, Harold.
Palmer, Lionel Stanley, M.Sc., Ph.D.
Payne, Lintorn Simmons.
Robinson, Wykeham Amyas A.
Wilton, Noel Valentine S.

Graduates.

Ahern, Patrick Joseph.
Aspinall, Henry Turner, B.Sc.(Eng.).
Bennett, David.
Beringer, Paul.
Best, Frederic Lafargue.
Dart, Frederick Harold.
George, Philip Herbert F.
Graham, Reginald Christopher M.
Gray, Walter Douglas.
Griffith, Ronald George.
Gupta, Karuna Kumar D.
Hebbert, Reginald James.
Highway, Frank Gordon, Lieut., R.E.
Hodge, Gilbert Woffinten.
Holden, George Cuthbert.
McLaughlin, Cecil James S.
Nagarajan, Tirupattur Krishnaswami.
Perkins, Thomas Ewart.
Robinson, Leonard Mansfield.
Scriven, Ernest.
Skinner, Arthur Cyriac.
Smith, Sydney Steele.
Wallcroft, Frederick Ernest.
Walters, George.
Wicks, Percy, B.Sc.
Wylie, Alexander Fleming.

Students.

Abrahams, Hyman.
Adams, John Ludford.
Addis, Edwin.
Allcock, Walter.
Baker, Richard Noel.
Barfoot, Rene Morison.
Barnes, Philip Carrington.
Belcher, Douglas Gordon.
Bond, Dudley Hales T.
Burdes, Leonard.
Bush, George Robert S.
Cansdale, John Henry.
Capper, John Frederick.
Catterall, Gerald.

Students—continued.

Cawte, Charles William.
Chadwick, Leonard Mark.
Christy, Geoffrey.
Chynoweth, Frederick.
Clark, John.
Cox, Francis George.
Cox, Robert Leonard.
Dalman, Frederick Narborough, B.Sc.(Eng.).
de Bejar, Alfonso Antonio L.
Dixon, George Skene.
Drury, George John S.
Fall, James William L.
Fletcher, Charles Bickham H.
Gomes, Carlos.
Gregory, Maxwell Justin, B.A.
Gupta, Sashanka Shekhor.
Halford, Richard.
Hardy, Arthur.
Harwood, Edward Holroyde.
Hilton, Rupert Polack.
Hoban, Hugh Charles.
Holbeche, Edgar Charles.
Holmes, Malcolm Graham.
Hunter, Herbert Leonard J.
Hutchins, Philip Perceval P.
Jackson, Frederick Samuel.
Jones, Gilbert Louis R.
Jose, Cyril Edwin P.
Kaye, Joseph Blamires.
Keene, James Kenneth.
Lawson, Reginald Percy.
Lea, Jeffrey Tunstall.
Merrie, Alexander Hardie.
Metcalf, Herbert Eustace L.
Milliken-Smith, Herbert.
Morley, John Lawrence.
Musgrave, William Leslie.
Needham, Arthur Wheeldon.
Nicholson, Thomas Croft.
Panikkar, Sankaran Narayana.
Pank, John Cornaby.
Powell, Reginald Alfred.
Richardson, Harry Carr.
Riley, Frank George M.
Ryland, Leslie Francis.
Sanjana, Kershasp Manekji.
Simmonds, Richard Samuel.
Sims, Lionel George A.
Smith, William Horace.
Spencer, Alfred Nicholas.
Thorpe, Leslie Jack.
Wilson, Ian Mackenzie.
Woodbine, Geoffrey Palmer.
Wood, Albert Gallatin.
Yates, John Penderel.

TRANSFERS.

Associate Member to Member.

Morris, Alfred Thomas.
Staniar, Henry Drummond, Capt., R.A.F.
Tate, Leonard George.
Wheeler, Roland.
Wood, William Wellesley.

Graduate to Associate Member.

Ross, Eric Graham.
Ross, Thomas Wylie.

Student to Associate Member.

Colquhoun, James.
Johns, John Percy.
Radley, William Gordon, B.Sc.(Eng.).

Associate to Associate Member.

Chaster, Clifford Stilwell.

Student to Graduate.

Cooper, Cyril Hoare.
Davies, Tracy Rees.
Friendship, Cyril Arthur.
Harmsworth, Harry Brooke.
Henderson, George Parker.
Hodgson, Charles Henry.
Morgan, Hedley Edmund.
Morrison, James Douglas.
Payne, George Lewis.
Sen, Ranjit Chandra.
Swinney, John.

The discussion on "Loud-Speakers for Wireless and other Purposes" (see pages 265 and 373) was continued, and the meeting terminated at 7.55 p.m.

A VECTOR TREATMENT OF LONG TRANSMISSION LINES.*

By S. HOLMES, Associate Member.

(*Paper first received* 13*th October, and in final form* 22*nd December*, 1923.)

TABLE OF CONTENTS.

1. INTRODUCTION.

In teaching the elementary principles of transmission, the author has found that students understand better what is happening in the transmission lines if a vector method is employed, rather than the method involving the use of complex quantities. It is thought that perhaps this method may be useful to others who are studying the subject for the first time, especially as there is little to choose between the accuracy of the two methods, since each has the equations of the transmission line as its starting-point.

All the currents are separated into their active and idle components respectively in phase and in quadrature with the voltage at the load or receiver end of the lines. Also, the impedance of the line is separated into its resistance and reactance components, so that when each is multiplied by a current the resulting voltage-drops in the line are respectively in phase and in quadrature with that current (see Fig. 1).

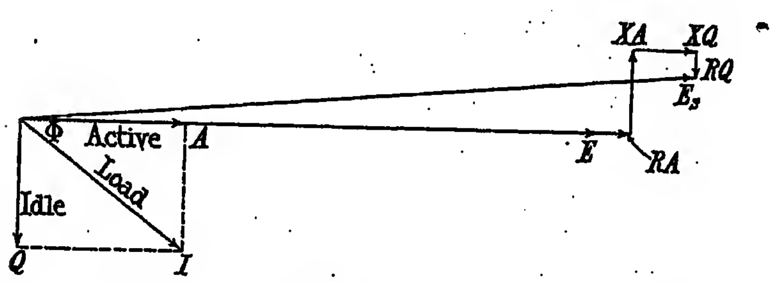

FIG. 1.—Diagram showing the load current separated into its active and idle components, with their corresponding resistance and reactance pressure-drops.

2. SYMBOLS.

E_s = voltage at the supply end of the line.
I_s = current at the supply end of the line.
E = voltage at the receiver end of the line.
I = current at the receiver end of the line.
I_N = minimum idle current supplied by the synchronous condenser for constant-voltage transmission.
I_c = line charging current, and is obtained from the product of B and E, where
B = shunted line susceptance, and is equal to the product of 2π, the frequency and the capacity of one line to earth.*
Z = impedance of one line, and is equal to $\sqrt{(R^2 + X^2)}$, where
R = resistance of one line, and
X = reactance of one line, and is equal to the product of 2π, the frequency and the inductance of one line.
s = spacing of the conductors.
r = radius of the conductors.

3. THE EQUATIONS OF THE TRANSMISSION LINE.

Owing to the distributed nature of the resistance, the inductance and the capacity of the lines, the current and the voltage equations form a converging series.

Neglecting line leakage, the voltage equation is expressed by

$$E_s = E(1 + \tfrac{1}{2}BZ + \frac{1}{2\,.\,3\,.\,4}B^2Z^2 + \ldots)$$
$$+ ZI(1 + \frac{1}{2\,.\,3}BZ + \frac{1}{2\,.\,3\,.\,4\,.\,5}B^2Z^2 + \ldots)$$

and, by omitting all terms beyond $B^2Z^2/(2\,.\,3\,.\,4)$ as negligible in practice, we get

$$\begin{aligned} E_s &= E(1 + \tfrac{1}{2}BZ + \tfrac{1}{24}B^2Z^2) + ZI(1 + \tfrac{1}{6}BZ) \\ &= E + \tfrac{1}{2}EBZ + (\tfrac{1}{4}EBZ)\tfrac{1}{6}BZ + ZI + ZI\tfrac{1}{6}BZ \\ &= E + ZI + Z(\tfrac{1}{2}EB) + Z\{Z(I + \tfrac{1}{4}EB)\tfrac{1}{6}B\} \\ &= E + ZI + Z\tfrac{1}{2}I_c + Z\{Z(I + \tfrac{1}{4}I_c)\tfrac{1}{6}B\} \\ &= E + Z\{(I + \tfrac{1}{2}I_c) + Z(I + \tfrac{1}{4}I_c)\tfrac{1}{6}B\} \end{aligned}$$

The voltage at the supply end of the line is equal to the vector sum of :—

(i) E, the voltage at the receiver end of the line.

(ii) ZI, the line impedance-drop due to the load current I.

(iii) $Z\tfrac{1}{2}I_c$, the line impedance-drop due to the average line charging current, $\tfrac{1}{2}I_c$. This current is of such a value as would be obtained by concentrating one-half of the line capacity at the receiver end of the line in parallel with the load, and is a quarter-cycle ahead of the receiver voltage E.

(iv) $Z\{Z(I + \tfrac{1}{4}I_c)\tfrac{1}{6}B\}$, the line impedance-drop due to the increase in the charging current, $Z(I + \tfrac{1}{4}I_c)\tfrac{1}{6}B$, caused by the rise in voltage, $Z(I + \tfrac{1}{4}I_c)$, from the receiver end to the supply end of the line.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

* Wkenever a vector is multiplied by B, it is advanced through a quarter cycle.

Similarly the current equation

$$I_s = I(1 + \tfrac{1}{2}BZ + \frac{1}{2.3.4}B^2Z^2) + BE(1 + \frac{1}{2.3}BZ)$$

can be expressed as

$$I_s = I + I_c + Z(I + \tfrac{1}{3}I_c + ZI\tfrac{1}{12}B)\tfrac{1}{2}B$$

The current at the supply end of the line is equal to the vector sum of :—

(v) I, the load current.

(vi) I_c, the total line charging current, which is of such a value as would be obtained by concentrating the whole of the line capacity at the receiver end of the line in parallel with the load, and is a quarter-cycle ahead of the receiver voltage E.

(vii) $Z(I + \frac{1}{3}I_c + ZI\frac{1}{12}B)\frac{1}{2}B$, the increase in the charging current due to the rise in voltage from the receiver end to the supply end of the line.

4. Calculation for a 250-mile, 110 000-volt Transmission Line.

A three-phase transmission line 250 miles long delivers 15 200 kW at 110 000 volts, at 80 per cent power factor and at 50 cycles per second, along overhead lines of 37/0·083 copper cable, equilaterally spaced 144 inches apart.

Resistance of one line.

Diameter of cable = 0·584 inch; cross-sectional area = 0·2 sq. inch.

Resistance per mile at 50 cycles = 0·212 ohm.

Resistance of one line, $R = 0{\cdot}212 \times 250 = 53$ ohms.

Reactance of one line.

Inductance per mile $= 0{\cdot}0805 + 0{\cdot}741 \log (s/r) = 2{\cdot}076$ mH.

Reactance per mile $= 2\pi \times 50 \times 2{\cdot}076 \times 10^{-3} = 0{\cdot}652$ ohm.

Reactance of one line, $X = 0{\cdot}652 \times 250 = 163$ ohms.

Capacity susceptance of one line.

Capacity per mile $= 0{\cdot}0388/(\log s/r) = 0{\cdot}01442\ \mu$F.

Capacity per line $= 0{\cdot}01442 \times 250 = 3{\cdot}6\ \mu$F.

Capacity susceptance of one line, $B = 2\pi \times 50 \times 3{\cdot}6 = 1\,132$ micromhos.

Star voltage at receiver end of line.

$E = 110\,000/\sqrt{3} = 63\,520$ V.

Average line charging current.

Line charging current, $BE = 1\,132 \times 10^{-6} \times 63\,520 = 72$ A.

Average charging current, $\frac{1}{2}BE = \frac{1}{2}72 = 36$ A, a quarter-cycle ahead of E.

Load current.

Power per line = 15 200/3 = 5 067 kW.

$$\text{Current per line at 0·8 power factor} = \frac{5\,067 \times 1\,000}{63\,520 \times 0{\cdot}8}$$

= 100 A.

Active component in phase with $E = 0{\cdot}8 \times 100 = 80$ A.

Idle component a quarter-cycle behind $E = 0{\cdot}6 \times 100 = 60$ A.

Increase in the charging current, $Z(I + \frac{1}{4}I_c)\frac{1}{3}B$.

Active current in phase with $E = 80$ A.

Idle current a quarter-cycle behind $E = 60 - \frac{1}{4}72 = 42$ A lagging (see Table 1).

Multiplying each of these by $\frac{1}{3}B$ or $188{\cdot}7 \times 10^{-6}$ gives the corresponding currents a quarter-cycle in advance of their respective voltage-drops.

$11\,086 \times 188{\cdot}7 \times 10^{-6} = 2{\cdot}1$ A, a quarter-cycle ahead of E.

$10\,814 \times 188{\cdot}7 \times 10^{-6} = 2{\cdot}0$ A, in opposition to E.

Line current, $I + \frac{1}{2}I_c + Z(I + \frac{1}{4}I_c)\frac{1}{3}B$.

Active current = 80 − 2 = 78 A in phase with E.

Idle current = 60 − 36 − 2·1 = 21·9 A, a quarter-cycle behind E (see Table 2).

Total voltage-drop.—7 704 V in phase with E; 11 553 V a quarter-cycle ahead of E.

Supply voltage at full load.

$$E_s = \sqrt{\{(63\,520 + 7\,704)^2 + (11\,553)^2\}} = \sqrt{(71\,224^2 + 11\,553^2)}.$$

= 72 150 V (star).

$= 72\,150\sqrt{3} = 124\,900$ V (delta).

Current at the supply end of the line,

$$I + I_c + Z(I + \tfrac{1}{3}I_c + ZI\tfrac{1}{12}B)\tfrac{1}{2}B.$$

Load current.—80 A in phase with E; 60 A a quarter-cycle behind E.

Total charging current.—72 A a quarter-cycle ahead of E.

Increase in charging, etc., currents,

$$Z(I + \tfrac{1}{3}I_c + ZI\tfrac{1}{12}B)\tfrac{1}{2}B \text{ (see Table 3).}$$

Multiplying by $\frac{1}{12}B = 0{\cdot}00009433$ gives the corresponding currents :—

$14\,020 \times 0{\cdot}00009433 = 1{\cdot}32$ A a quarter-cycle ahead of E.

$9\,860 \times 0{\cdot}00009433 = 0{\cdot}93$ A in opposition to E.

Active current in phase with $E = 80 - 0{\cdot}93 = 79{\cdot}07$ A.

Idle current a quarter-cycle behind $E = 60 - \frac{1}{3}72 - 1{\cdot}32 = 34{\cdot}68$ A (see Table 4).

Multiplying by $\frac{1}{2}B = 0{\cdot}000566$ gives the corresponding currents :—

$9\,843 \times 0{\cdot}000566 = 5{\cdot}6$ A a quarter-cycle ahead of E.

$11\,051 \times 0{\cdot}000566 = 6{\cdot}3$ A in opposition to E.

Current at the supply end of line.

Active component in phase with $E = 80 - 6{\cdot}3 = 73{\cdot}7$ A.

Idle component a quarter-cycle ahead of $E = 72 + 5{\cdot}6 - 60 = 17{\cdot}6$ A.

Total current at supply end $= \sqrt{(73{\cdot}7^2 + 17{\cdot}6^2)} = 75{\cdot}8$ A leading by 4·2 degrees on the supply voltage E_s, since the supply voltage and the supply current are ahead of the receiver voltage by the angles whose respective tangents are 11 553/71 224 and 17·6/73·7.

5. Calculation for Constant-voltage Transmission.

For a constant receiver pressure of 110 000 volts, the supply voltage is 125 000 at full load and 100 000 at no load. In order to keep the voltage constant at

TABLE 1.

Component of current	Voltage-drop
Active, 80 A	Resistance, 80 × 53 = 4 240 V in phase with E
Idle, 42 A (lagging)	Reactance, 42 × 163 = 6 846 V in phase with E
	Total 11 086 V in phase with E
Active, 80 A	Reactance, 80 × 163 = 13 040 V $\frac{1}{4}$-cycle ahead of E
Idle, 42 A (lagging)	Resistance, 42 × 53 = 2 226 V $\frac{1}{4}$-cycle behind E
	Total 10 814 V $\frac{1}{4}$-cycle ahead of E

TABLE 2.

Component of current	Voltage-drop
Active, 78 A	Resistance, 78 × 53 = 4 134 V in phase with E
Idle, 21·9 A (lagging)	Reactance, 21·9 × 163 = 3 570 V in phase with E
	Total 7 704 V in phase with E
Active, 78 A	Reactance, 78 × 163 = 12 714 V $\frac{1}{4}$-cycle ahead of E
Idle, 21·9 A (lagging)	Resistance, 21·9 × 53 = 1 161 V $\frac{1}{4}$-cycle behind E
	Total 11 553 V $\frac{1}{4}$-cycle ahead of E

TABLE 3.

Component of current	Voltage-drop
Active, 80 A	Resistance, 80 × 53 = 4 240 V in phase with E
Idle, 60 A (lagging)	Reactance, 60 × 163 = 9 780 V in phase with E
	Total 14 020 V in phase with E
Active, 80 A	Reactance, 80 × 163 = 13 040 V $\frac{1}{4}$-cycle ahead of E
Idle, 60 A (lagging)	Resistance, 60 × 53 = 3 180 V $\frac{1}{4}$-cycle behind E
	Total 9 860 V $\frac{1}{4}$-cycle ahead of E

TABLE 4.

Component of current	Voltage-drop
Active, 79·07 A	Resistance, 79·07 × 53 = 4 190 V in phase with E
Idle, 34·68 A (lagging)	Reactance, 34·68 × 163 = 5 653 V in phase with E
	Total 9 843 V in phase with E
Active, 79·07 A	Reactance, 79·07 × 163 = 12 890 V $\frac{1}{4}$-cycle ahead of E
Idle, 34·68 A (lagging)	Resistance, 34·68 × 53 = 1 839 V $\frac{1}{4}$-cycle behind E
	Total 11 051 V $\frac{1}{4}$-cycle ahead of E

both ends of the line under all conditions of load, synchronous condensers are placed in parallel with the load at the receiver end of the line. The capacity of the synchronous plant is a minimum when it supplies the same current (I_N) both at no load and at full load. The current (I_N) is a quarter-cycle behind the receiver voltage at no load and a quarter-cycle ahead of it at full load.

(*a*) *At no load.*

Idle current $= I_N - 36$, a quarter-cycle behind E.

Increase in the charging current, $Z(I_N + \frac{1}{4}I_c)\frac{1}{8}B$.

Idle current $= I_N - \frac{1}{4}72 = I_N - 18$, a quarter-cycle behind E.

Resistance drop $= 53I_N - 954$, a quarter-cycle behind E.

Reactance drop $= 163I_N - 2\,934$, in phase with E.

Multiplying by $\frac{1}{8}B = 0{\cdot}0001887$ gives the corresponding currents :—

$(53I_N - 954) \times 0{\cdot}0001887 = (0{\cdot}01I_N - 0{\cdot}18)$ A in phase with E.

$(163I_N - 2\,934) \times 0{\cdot}0001887 = (0{\cdot}03I_N - 0{\cdot}55)$ A, a quarter-cycle ahead of E.

Line currents :—

Active current in phase with $E = (0{\cdot}01I_N - 0{\cdot}18)$.

Idle current a quarter-cycle behind E

$$= I_N - 36 - (0{\cdot}03I_N - 0{\cdot}55) = 0{\cdot}97I_N - 35{\cdot}45$$
(see Table 5)

$$E_s^2 = (63\,520 + 158{\cdot}5I_N - 5\,790)^2 + (49{\cdot}8I_N - 1\,850)^2$$
$$= (57\,730 + 158{\cdot}5I_N)^2 + (49{\cdot}8I_N - 1\,850)^2$$

(*b*) *At full load.*

Active current in phase with $E = 80$ A.

Idle current a quarter-cycle ahead of E

$$= (I_N + \tfrac{1}{2}72 - 60) = (I_N - 24)$$

Decrease in the charging current,

$$Z(I + I_N + \tfrac{1}{4}I_c)\tfrac{1}{8}B.$$

Active current in phase with $E = 80$ A.

Idle current a quarter-cycle ahead of E

$$= I_N + \tfrac{1}{4}72 - 60 = (I_N - 42) \text{ (see Table 6)}$$

Multiplying by $\frac{1}{8}B = 0{\cdot}0001887$ gives the corresponding currents :—

$(163I_N - 11\,086) \times 0{\cdot}0001887 = (0{\cdot}03I_N - 2{\cdot}1)$ A a quarter-cycle behind E.

$(53I_N + 10\,814) \times 0{\cdot}0001887 = (0{\cdot}01I_N + 2)$ A in opposition to E.

Line currents at full load,

$$I + I_N + \tfrac{1}{2}I_c + Z(I + I_N + \tfrac{1}{4}I_c)\tfrac{1}{8}B.$$

Active $= 80 - (0{\cdot}01I_N + 2) = (78 - 0{\cdot}01I_N)$ in phase with E.

Idle $= I_N - 24 - (0{\cdot}03I_N - 2{\cdot}1) = (0{\cdot}97I_N - 21{\cdot}9)$ a quarter-cycle ahead of E (see Table 7).

$$E_s^2 = \{63\,520 - (158{\cdot}5I_N - 7\,704)\}^2 + (49{\cdot}8I_N + 11\,553)^2$$
$$= (71\,224 - 158{\cdot}5I_N)^2 + (49{\cdot}8I_N + 11\,553)^2$$

Since the supply voltage is the same both at no load and at full load, by equating the two equations we get :—

$$(71\,224 - 158{\cdot}5I_N)^2 + (49{\cdot}8I_N + 11\,553)^2$$
$$= (57\,730 + 158{\cdot}5I_N)^2 + (49I_N - 1\,850)^2$$

and, on re-arranging,

$$(49{\cdot}8I_N + 11\,553)^2 - (49{\cdot}8I_N - 1\,850)^2$$
$$= (57\,730 + 158{\cdot}5I_N)^2 - (71\,224 - 158{\cdot}5I_N)^2$$

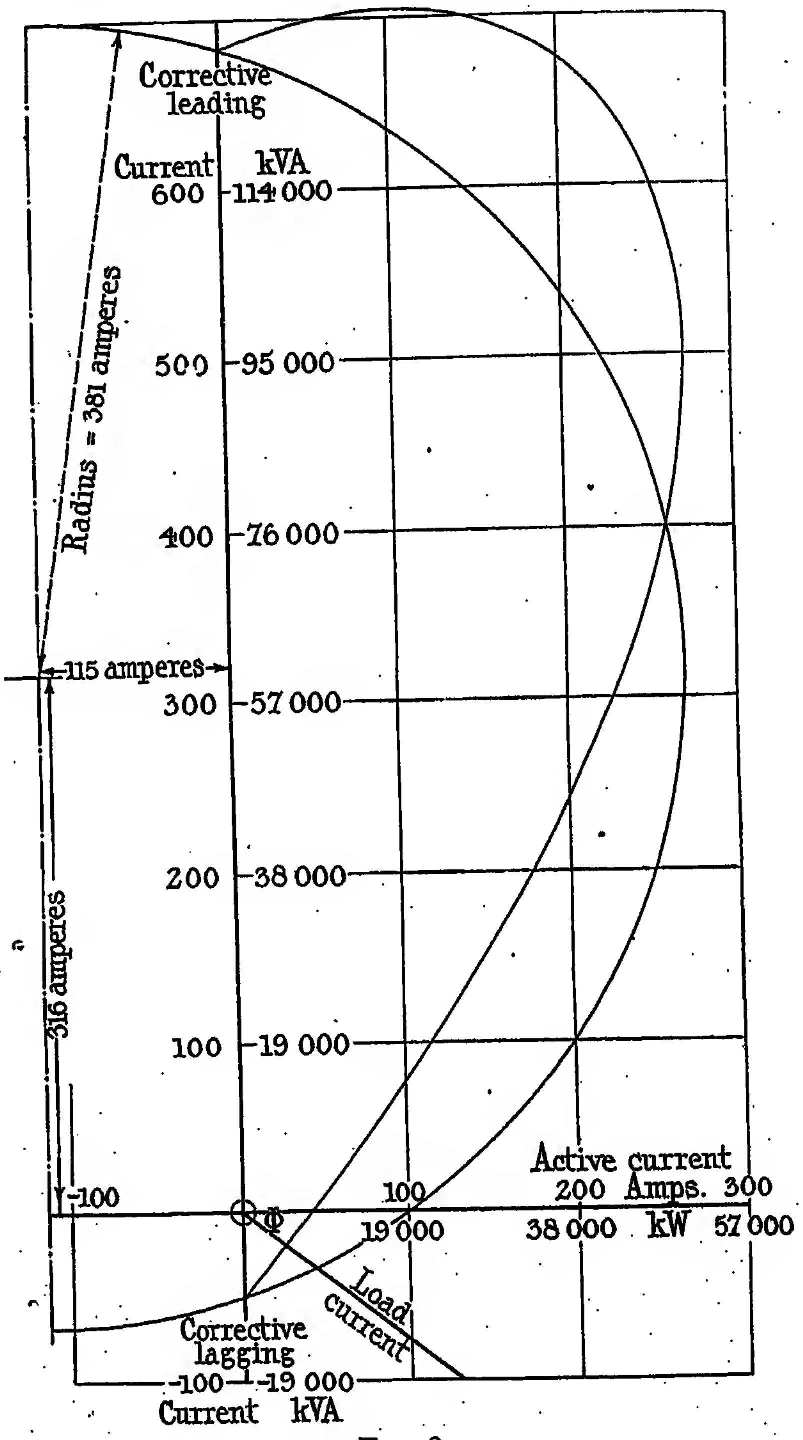

Fig. 2.

Since the difference of two squares is the product of the sum and of the difference of the two numbers forming the squares, we get :—

$$13\,403(99{\cdot}6I_N + 9\,703) = 128\,954(317I_N - 13\,494)$$
$$1{\cdot}33 \times 10^6 I_N + 13 \times 10^7 = 41 \times 10^6 I_N - 174 \times 10^7$$
$$39{\cdot}67I_N = 1\,870$$
$$I_N = 47 \text{ A}$$

The line corrective kVA $= 3 \times 47 \times 63\,520/1\,000 = 8\,960$, a quarter-cycle behind E at no load, and a quarter-cycle ahead of E at full load.

Voltage at supply end of line, $E_s = 65\,250$ V (star) $= 113\,000$ V (delta).

6. Calculation of the Circle Diagram (see Fig. 2).

$E_s = 65\,250$; $E = 63\,520$.

Active component of charging current at no load in phase with $E = 0{\cdot}01 I_N - 0{\cdot}18 = 0{\cdot}29$ A.

Idle component of charging current at no load a quarter-cycle behind E

$= 36 + (0{\cdot}03 I_N - 0{\cdot}55) = 36{\cdot}9$ A (from Section 5).

Solving, we get:—

$$29\,380 A^2 + 67\,520 \times 10^3 A + 29\,380 Q^2 - 185\,500 \times 10^2 Q = 94\,600 \times 10^4$$

$$\therefore\ A^2 + 230A + Q^2 - 632Q = 32\,270$$

$$(A + 115)^2 + (Q - 316)^2 = 32\,270 + 115^2 + 316^2 = (381)^2$$

TABLE 5.

Component of current	Voltage-drop		
Active, $(0{\cdot}01 I_N - 0{\cdot}18)$ A	Resistance,	$0{\cdot}53 I_N -$ 10 V	in phase with E
Idle (lagging), $(0{\cdot}97 I_N - 35{\cdot}45)$ A ..	Reactance,	$158{\cdot}0 I_N -$ 5 780 V	in phase with E
	Total	$158{\cdot}5 I_N -$ 5 790 V	in phase with E
Active, $(0{\cdot}01 I_N - 0{\cdot}18)$ A	Reactance,	$1{\cdot}63 I_N -$ 29 V	$\frac{1}{4}$-cycle ahead of E
Idle (lagging), $(0{\cdot}97 I_N - 35{\cdot}45)$ A ..	Resistance,	$51{\cdot}4 I_N -$ 1 879 V	$\frac{1}{4}$-cycle behind E
	Total	$49{\cdot}8 I_N -$ 1 850 V	$\frac{1}{4}$-cycle behind E

TABLE 6.

Component of current	Voltage-drop			
Active, 80 A	Resistance,	80×53 =	4 240 V	in phase with E
Idle (leading), $(I_N - 42)$ A	Reactance,	$163(I_N - 42) = 163 I_N -$	6 846 V	in opposition to E
		Total	$163 I_N -$ 11 086 V	in opposition to E
Active, 80 A	Reactance,	80×163	13 040 V	$\frac{1}{4}$-cycle ahead of E
Idle (leading), $(I_N - 42)$ A	Resistance,	$53(I_N - 42) = 53 I_N -$	2 226 V	$\frac{1}{4}$-cycle ahead of E
		Total	$53 I_N +$ 10 814 V	$\frac{1}{4}$-cycle ahead of E

TABLE 7.

Component of current	Voltage-drop		
Active, $(78 - 0{\cdot}01 I_N)$ A	Resistance,	$4\,134 - 0{\cdot}53 I_N$ V	in phase with E
Idle (leading), $(0{\cdot}97 I_N - 21{\cdot}9)$ A ..	Reactance,	$158 I_N -$ 3 570 V	in opposition to E
	Total	$158{\cdot}5 I_N -$ 7 704 V	in opposition to E
Active, $(78 - 0{\cdot}01 I_N)$ A	Reactance,	$12\,714 - 1{\cdot}63 I_N$ V	$\frac{1}{4}$-cycle ahead of E
Idle (leading), $(0{\cdot}97 I_N - 21{\cdot}9)$ A ..	Resistance,	$51{\cdot}4 I_N -$ 1 161 V	$\frac{1}{4}$-cycle ahead of E
	Total	$11\,553 + 49{\cdot}8 I_N$ V	$\frac{1}{4}$-cycle ahead of E

Let A be the active current in the line at the receiver end in phase with E, and

Q be the idle current in the line at the receiver end a $\frac{1}{4}$-cycle ahead of E.

$$65\,250^2 = \{63\,520 + 53(A + 0{\cdot}29) - 163(Q + 36{\cdot}9)\}^2 + \{163(A + 0{\cdot}29) + 53(Q + 36{\cdot}9)\}^2$$

$$= (57\,520 + 53A - 163Q)^2 + (163A + 53Q + 2\,000)^2$$

This is the equation to a circle whose centre is at a point the ordinates of which are − 115 and 316 amperes and whose radius is 381 amperes.

Multiplying each by $(3 \times 63\,520)/1\,000$ gives the circle showing the relation between the kilowatts and the corrective idle kilovolt-amperes required by the line for constant-voltage transmission.

The synchronous plant at the receiver end of the

line has to supply corrective idle kilovolt-amperes to the load as well as to the line. By drawing in the load-current line at its correct angle of lag, the curve connecting the load in kilowatts and the idle kilovolt-amperes of the synchronous plant is obtained, and is found to be an ellipse.

7. Bibliography.

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DISCUSSION ON
"AN INVESTIGATION OF THE FRICTION BETWEEN SLIDING SURFACES." *

Mr. O. R. Randall (*communicated*): On page 151, while dealing with the resistance of a system containing a semi-conductor, the author states: "As far as we are aware no attempt has been made to distinguish between body and contact resistance." Experiments carried out at Birmingham University have been successful in separating contact resistance from the other factors involved in the problem. It was found during the course of the work that, in order to determine the part played by the contact, it was necessary to consider all the following quantities: (*a*) The resistance of the stone up to a plane very near the contact; (*b*) the resistance of the thin layer of stone near the contact; (*c*) the capacity across the contact; and (*d*) the resistance of the leak across the capacity. It will be seen that the resistance of the contact can mean either the true resistance across the interface between the conducting surfaces, or the resistance of this region added to the resistance of the adjacent layer of stone. The separation of these two resistances without introducing capacity was very difficult, as it was found that they varied together, and under most test conditions none of the quantities mentioned in (*a*), (*b*), (*c*) and (*d*) above is constant. The method used to separate the resistance of the body of the stone, not including the layer very near the contact, from the resistances (*b*) and (*d*) added together, was as follows: A group of similar contacts was placed at each end of a large slab of stone, and while a unit contact was left connected to one pole of the supply, at the other end the contacts in parallel were gradually increased, the current meanwhile being kept constant until, on further increasing the area, there was no change in the current. When this condition was reached the total voltage decrement needed to maintain constant current measured the initial resistance-drop across the unit contact, which the process had eliminated. A great many tests were carried out with various modifications of this general plan, and the results clearly showed that the resistance of the body of the stone, together with any back E.M.F., was in general only 2 or 3 per cent of the whole resistance of the system. An interesting result of these tests was that it was shown that the total contact drop [including (*b*) and (*d*) above] was not the same for the two ends of the system, the contact connected to the negative end of the supply always showing a larger voltage drop than the contact connected to the positive end. Representative figures are given below showing the values found in two tests:—

Test A.

Current = 0·27 micro-amperes.
Voltage across positive contact and adjacent layer of stone = 9·7 volts.
Voltage across negative contact and adjacent layer of stone = 15·2 volts.
Back E.M.F. plus the resistance in the body of the stone = 1·5 volts.

Test B.

Current = 0·18 micro-amperes.
Voltage, positive, as above = 6·9 volts.
Voltage, negative, as above = 11·0 volts.
Voltage in body of stone and back E.M.F. = 1·1 volts.

In the above experiments, as in all those dealt with in this contribution, the contacts were formed by tinfoil on lithographic stone. The results of these tests were important in connection with the experiments carried out to separate the quantities mentioned in (*a*), (*b*), (*c*) and (*d*) above, since they showed that by making one contact large compared with the other, its effect would be correspondingly small. Using this principle a circuit was arranged in which one of the contacts was so much larger than the other that all the voltage of the system could be assumed to be distributed over the region of the smaller contact. This small contact was treated as a condenser in series with a high resistance (the layer of stone near the contact) and shunted by another high resistance (the true resistance across the interface). These tests were more difficult to analyse than the last, because it was necessary to introduce time as another variable, and there were progressive changes in the value of the quantities being measured. Consistent results were obtained, however, and the results of a representative test are as follows:—

Resistance of layer of stone near contact = 195 megohms.
Resistance across contact = 98 megohms.
Capacity = 1·4 microfarads.
Area of contact = 2 cm².

In connection with the resistance of the stone itself, experiments have been carried out using a prism of lithographic stone machined to a uniform section and long compared with its width and depth. At the ends large contacts were placed, and bands of tinfoil were fixed round the middle part, separated by a known distance; these test-contacts were connected to a standard condenser, which was charged over a length of time found by experiment to be long enough to eliminate the effect of the contact resistance at the test or charging contacts. The condenser could be discharged through a ballistic galvanometer, and so the potential difference between the test-contacts could be determined. A knowledge of the current in the circuit then gave the value of the resistance between the test-contacts. This apparatus gave very consistent results, and by its means the effects of temperature and moisture were investigated. The result of temperature-changes was very interesting: the tests showed that the specimen had a resistance/temperature rate of change equal to 2 megohms per degree C. between the limits of temperature reached in the tests. This was about 6 per cent of the average initial resistance, and indicates that the material would have quite a low resistance if the temperature were raised through a range easily realized in a laboratory (the tests are not yet completed). It should be noted

* Paper by Dr. H. M. Barlow (see page 133).

that this does not mean that the resistance of the set as a whole is reduced to this extent, since the contact resistance gives the character to the whole set.

The author states on page 151: "By testing various thicknesses of a particular sample of semi-conductor, the body and contact resistance are easily separated." My experience makes me doubt the reliability of the method proposed, as it has been found that small variations in contact conditions are sufficient to mask the changes in resistance which it is intended to estimate. The method was tried during the preliminary tests, and it was given up because of the objection stated. In several places the author mentions the effect of wetting the contact, and yet he washed the samples of lithographic stone before using them. During the course of the experiments described above it has been found that the effect of wetting a stone, or even of making the air in the room very wet, was gradually to alter the resistance of the stone, and that the change sometimes took place over several days. In view of these observations, it seems doubtful if one hour's drying after washing would result in uniform initial conditions.

Dr. H. M. Barlow (*in reply*): The experiments carried out by Mr. Randall are very interesting and, although I cannot agree with him in the procedure he has adopted, it is satisfactory to observe that he has arrived at the same general result as I did, namely, that the effective body resistance of lithographic stone is only a small part of the total resistance between the electrodes. In the first place it seems to me that to treat the thin layer of stone near the contact as a separate entity is simply to introduce unnecessary complications. There is no reason to suppose that the surface layer of the stone differs in constitution from the internal layers, or that there is any discontinuity between these layers. It is true that the bounding surface will be pitted and thus have an irregular contour, but it is largely in virtue of these irregularities that the contact acts as a condenser. It would appear, therefore, that the true contact resistance is simply in parallel with the interface capacity, and the hypothetical series resistance is really a part of the body resistance of the stone. The description of the experiments with the unit contacts is rather difficult to follow, but, as I understand it, the number of parallel contacts at one pole is gradually increased until the resistance of this connection is relatively negligible. Then the total amount by which the applied potential difference has been reduced to maintain a constant current is equal to the product of this current and the resistance of the unit contact. In my view the accuracy of this deduction depends entirely on the unit contacts having the same resistance. Mr. Randall points out that my experiments with various thicknesses of semi-conductor are inclined to give misleading results on account of variations in the contact conditions. He states that he abandoned this method on account of these difficulties, but it appears to me that his tests with the unit contacts suffer from precisely the same objection, which would be specially marked with the tinfoil electrodes employed. Moreover, apparently no allowance is made for the necessary variations in the distance between the two poles, the influence of the capacity of the contacts, and the gradually increasing back E.M.F. due to absorption. My experiments in this direction show that a long time is required to establish steady conditions even with a small contact.

The method employed for determining the internal resistance of the stone is distinctly ingenious and is independent of the nature of the contact. I cannot, however, agree with Mr. Randall that the surface layer of stone is not included in these measurements. Since the current only flows longitudinally when the steady state is reached, it must distribute itself over the whole cross-section of the prism. Theoretically, an infinite time is required to reach the final condition when the P.D. across the standard condenser should be measured, but I have no doubt that reasonable accuracy can be obtained in practice after a few hours' charging. It appears difficult to calculate the specific resistance of the material from the data obtained. The back E.M.F. due to absorption and surface leakage must also be involved in these measurements. When further details of Mr. Randall's work are available, I shall welcome an opportunity of a more detailed discussion.

INSTITUTION NOTES.

Mascart Medal.

The Société Française des Electriciens have founded a Medal of Honour to be called the Mascart Medal, in memory of that eminent French scientist, the Medal to be awarded triennially to scientists or engineers of any nationality distinguished for their work in pure and applied electricity. The first (1924) award of the Medal has been made to Monsieur A. Blondel, an Honorary Member of the Institution.

War Thanksgiving Education and Research Fund (No. 1).

The grant for 1924 in connection with the above Fund has been made by the Council to Mr. Alexander Ramsay, of Glasgow University.

Portrait of the late Mr. Willoughby Smith.

Mr. W. O. Smith and Mr. W. S. Smith, Members, have presented to the Institution an oil painting of the late Mr. Willoughby Smith, who was President of the Institution in 1883.

Associate Membership Examination Results: February, 1924.

OFFICERS OF THE ROYAL CORPS OF SIGNALS.

Passed.

Anthony, Lieut. H. H. (17th Pack Battery, R.G.A.).
Childs, Lieut. C. (R.F.A.).
Glover, Lieut. H. P. McC. (R.F.A.).
Harris, Lieut. E. H. C. (Royal Sussex Regt.).
Hart, Lieut. H. P. (R.F.A.).
Herdon, Lieut. W. F. (1/13 F.F. Rifles, I.A.).
Higgs, Capt. R. M. (4th Rajputs, I.A.).
Jones, Capt. G. F. [18th (K.E.O.) Cavalry, I.A.].
Loftus-Tottenham, Capt. F. J. (2/2nd Gurkha Rifles, I.A.).
Malden, Capt. C. M. (6/13th F.F. Rifles, I.A.).
Moreton, Capt. E. A. (3rd Battn. 17th Dogra Regiment, I.A.).
Mulligan, Lieut. A. D. (K.O.Y.L.I.).
Nicholls, Lieut. L. B. (R.A.S.C.).
Rogers, Lieut. W. H. G. (R.F.A.).
Solly, Lieut. R. J. N. (Yorks. and Lancs. Regt.).
Thursby-Pelham, M.C., Lieut. C. K. (King's Own Scottish Bdrs.).
Watson, Lieut. L. R. C. (Northumberland Fusiliers).

Informal Meetings.

The following Informal Meetings have been held :—

48TH INFORMAL MEETING (7TH JANUARY, 1924).

Chairman : Dr. H. M. Barlow.

Subject of Discussion : "Troubles experienced with Domestic Electrical Appliances" (introduced by Mr. J. W. Beauchamp).

Speakers : Messrs. A. F. Harmer, M. Pulvermacher, A. W. Blake, W. P. Fanghanel, F. Selley, M. Napier Prentice, E. E. Sharp, W. L. Wreford, E. W. Lovell, W. Betts, R. Grierson, F. J. E. Nesbitt, and C. E. Charman.

49TH INFORMAL MEETING (21ST JANUARY, 1924).

Chairman : Mr. R. Grierson.

Subject of Discussion : "Broadcasting" (introduced by Mr. E. H. Shaughnessy, O.B.E.).

Speakers : Messrs. G. F. Bedford, C. F. Phillips, W. H. Lawes, H. J. Neill, P. Voigt, J. Coxon, W. E. Warrilow, W. Day, E. G. Bedford, J. R. Bedford, E. S. Ritter, and R. Grierson.

50TH INFORMAL MEETING (4TH FEBRUARY, 1924).

Chairman : Mr. A. F. Harmer.

Subject of Discussion : "Storage Battery Troubles" (introduced by Mr. F. W. Crawter).

Speakers : Messrs. W. R. Rawlings, J. W. Beck, J. R. Bedford, F. C. Raphael, A. G. Hilling, K. L. Wood, R. V. Hook, F. A. Sclater, W. A. Ritchie, W. R. Cooper, and A. F. Harmer.

51ST INFORMAL MEETING (18TH FEBRUARY, 1924).

Chairman : Mr. F. Gill.

Subject of Discussion : "Electrical Development in France" (introduced by Mr. E. M. Malek).

Speakers : Colonel T. Rich, Messrs. G. L. Addenbrooke, W. E. Rogers, A. C. Sparks, W. J. Minton, A. G. Hilling, J. Coxon, A. W. Berry, S. W. Melsom, R. A. MacMahon, R. V. Hook, R. Grierson, and A. R. Rendall.

52ND INFORMAL MEETING (3RD MARCH, 1924).

Chairman : Mr. E. F. Hetherington.

Subject of Discussion : "The Selection and Location of Converting Plant for Supplying D.C. Networks" (introduced by Mr. R. D. Spurr).

Speakers : Messrs. W. E. Rogers, H. Craske, A. F. Harmer, C. M. Mayson, E. F. Hetherington, A. G. Hilling, R. V. Hook, A. H. E. Tomkinson, and R. Grierson.

53RD INFORMAL MEETING (10TH MARCH, 1924).

Chairman : Mr. A. G. Hilling.

Subject of Discussion : "The Work of the International Conference on E.H.T. Lines held in Paris, November 1923" (introduced by Mr. J. Tribot Laspière).

Speakers : Messrs. R. Borlase Matthews, W. E. Rogers, P. V. Hunter, C.B.E., A. Jacob, E. H. Rayner, J. Coxon, Prof. C. L. Fortescue, Messrs. K. Edgcumbe, P. Dunsheath, O.B.E., and P. Good.

54TH INFORMAL MEETING (17TH MARCH, 1924).

Chairman : Mr. A. F. Harmer.

Subject of Discussion : "Illuminating Engineering, its Application and Value to the Electrical Industry" (introduced by Messrs. L. Gaster and J. S. Dow).

Speakers : Messrs. J. Eck, P. Good, W. E. Bush, W. Day, A. Cunnington, W. P. Fanghanel, J. Coxon, P. Dunsheath, O.B.E., J. R. Bedford, and E. W. H. Wilson.

55TH INFORMAL MEETING (31ST MARCH, 1924).

Chairman : Mr. F. Pooley.

Subject of Discussion : "Economics in Engineering" (introduced by Mr. F. Gill).

Speakers : Messrs. D. J. Bolton, W. E. Rogers, W. Day, B. O. Anson, S. W. Pook, P. Dunsheath, O.B.E., L. M. Jockel, P. Good, H. M. Sayers, E. S. Byng, F. Tremain, and H. Brown.

56TH INFORMAL MEETING (14TH APRIL, 1924).

Chairman : Mr. W. E. Warrilow.

Subject of Discussion : "Some Idiosyncrasies of Electrical Manufacturers" (introduced by Mr. J. R. Bedford).

Speakers : Messrs. J. Coxon, W. Day, P. Rosling, W. E. Rogers, J. F. Avila, D. Dixon, A. Kirk, W. L. Wreford, H. Brown, F. P. Sexton, W. E. Twells, F. Pooley, J. T. Bedford, C. F. Mounsdon, W. Riggs, A. F. Harmer, A. G. Hilling, M. Whitgift, R. V. Hook, V. N. Halliday, and W. E. Warrilow.

The Benevolent Fund.

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SOME RESEARCHES ON THE SAFE USE OF ELECTRICITY IN COAL MINES.

By Professor W. M. THORNTON, O.B.E., D.Sc., D.Eng., Member.

(*Paper first received* 18*th September, and in final form* 22*nd November,* 1923; *read before* THE INSTITUTION 31*st January, before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 14*th January, before the* NORTH-EASTERN CENTRE 28*th January, before the* NORTH-WESTERN CENTRE 19*th February, before the* SOUTH MIDLAND CENTRE 12*th March, before the* NORTH MIDLAND CENTRE 18*th March, before the* SCOTTISH CENTRE 9*th April, and before the* WESTERN CENTRE 3*rd May,* 1924.)

SUMMARY.

The limiting electrical conditions under which ignition of coal dust and firedamp may occur have been worked at in the author's laboratory for the past 14 years, as part of a general investigation of the mechanism of ignition of gases. The paper contains an account of some results of practical interest, and deals with the electrical ignition of coal dust alone, coal dust with gas present, of methane and associated gases by disruptive sparks, steady or impulsive, transient arcs, direct or alternating, with varied voltage and frequency, in all percentages of mixture with air. Examples are given of the application of the results to promote safety in mines, notably the influence of currents of higher frequency than usual, of safety bells, safety lamps which give an alarm signal when dangerous mixtures of gas occur, and an improved earthing plate.

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(1) INTRODUCTION.

Electricity is the perfect medium for conveying energy underground. Its advantages are clear to all, but, like other systems, it has limits. There is the possibility of leakage, from which in the old days shocks were not uncommon, and there is the electric spark. It used to be held that every visible spark would fire an explosive gaseous mixture. One of the objects of the paper is to show how far this is from the truth and to define the limits within which the safe use of electricity is possible for the various purposes of mining. The researches of which a brief account is now given were started after the West Stanley, Hulton and Senghenydd Colliery explosions, to find an answer to the many questions more or less directly raised as to the risk of ignition from electrical causes. At that time a vague unrest was felt about the working conditions of electricity in mines, but little or nothing was known of the influence of the various factors in the problem, of voltage, frequency, metal of poles, gas pressure, capacity, inductance, and frequency. Considering the immense importance of the issues involved and the necessity for precise knowledge, it seemed worth while to enter on the laborious task of determining the critical limits in each of the above cases. Every engineer knows that only by accurate measurement of the breakdown values of the materials that he uses can safety be ensured. In the present work the breaking point is the current or voltage which just causes ignition, other factors being systematically varied or kept constant. The alternative to such investigation is to wait for the event, hold an Inquiry and act upon the finding. The cost in life and material of such a method is high and, so far as electricity is concerned, need never be paid if the human element of carelessness could be for ever removed, for to each possibility of electrical risk there is a simple and effective preventive.

The inflammable part of pit gas in this country is methane (CH_4), the lowest and most inert of the paraffin series of compounds. It is to this inertness that coal-mining owes the greater part of its immunity from explosions. Most of the accidents in mines are mechanical in origin, and are due to the poor illumination on haulages, or to the difficulty of keeping earth movements under continual observation. Safety in coal mines, now and in the future, depends on efficient ventilation (already excellent), the elimination of all sources of flame or open sparking, the improvement of underground illumination, not so much at the face as along the roads, and on the training into habits of constant observation and carefulness of those upon whom the getting of coal depends.

The growth of the use of electricity in mining followed closely that in other forms of industry, but, when it is considered that only 11 per cent of the coal raised in England and Wales is cut by electrical machines, there is room for expansion. Scotland alone cuts 36 per cent mechanically; but it is in electrical haulage that development is likely to be greatest. The electrical age in mining began in the early eighties, and it may be noted that in the Report of the Prussian Firedamp Commission * of 1881, made in 1887, there were no cases on record of accident from the use of electricity. Of the total number of explosions, 56·8 per cent were due to naked lights, and 14·6 to shot-firing. This Report is noteworthy for the section, 56, on Ignition by Electric Sparks, by Professors Wüllner and Lehmann,

* Translated by Professor P. Phillips Bedson.

of Aachen, which was really an inquiry preliminary to using electricity on a large scale underground. Their experiments did not go very far but established several interesting facts. Long sparks from an electrophorus would not fire pit gas, nor would bright condenser discharges. Certain least igniting currents are given, 18 amperes in one case, but voltage is not mentioned. Mallard and Le Chatelier had previously investigated ignition by hot wires, and had given many instances of the failure of ignition by wires at temperatures approaching the melting point of silver, which were confirmed and extended by Wüllner and Lehmann. In 1904 a British Departmental Committee was appointed by the Home Office and special rules * were formulated as a result of the evidence, but the rapid introduction of electricity into coal mines from 1895 onward, and the not altogether satisfactory manner of its installation, gave rise to a further committee in 1910 to investigate the working of the special rules. The Report † (3) of this latter committee and the rules as modified by it may be regarded as the Reform Bill of electricity in mining so far as British practice is concerned. Open sparking of any kind is prohibited, flame-proof gear specified, and armouring and its earthing insisted upon. In effect, electricity was put on a level with naked lights and was not to be used when more than 1¼ per cent of gas was present. Everything was considered but signalling bells, whose sparks were not regarded as being dangerous. They soon after received attention.

Three great colliery disasters occurring at short intervals, i.e. West Stanley (Durham) in 1909, Hulton (Lancashire) in 1910, and Senghenydd (South Wales) in 1913, the last with a death-roll of 439 (the greatest on record), each directed attention during the Inquiry to possible weaknesses in the electrical equipment of collieries, which have now been rectified. The specification of flame-proof apparatus with wide metal-to-metal flanges and bushes, covers the first two cases, and the provision of signalling bells the spark of which is made inert in various ways is enforced by the third, of which a sparking bell was the suspected cause.‡

(2) Inflammable Gas and Dust.

All but a few colliery explosions have begun by ignition of gas. With modern ventilation, gas cannot collect in mixtures rich enough to transmit a continuous explosion throughout the workings. Local ignitions may result in nothing more than a burst of flame, burning those in contact with it. In an enclosed space the pressure may rise to about eight atmospheres, but if the place opens into a road with larger volume not full of gas the pressure-rise is not so great; there must be constraint for pressure to develop. If, however, there is coal dust thrown down from the roof and ledges by the sound or pressure wave of such a local explosion, quickly enough to be caught in the first rush of flame, there is probability of transition to the much more dangerous form of explosion of coal dust alone. This dust is present everywhere through the workings and all the great disasters have been dust explosions, ignited in most cases by a small gas explosion. First proved by Professor W. Galloway * in 1884, it is only within the past 20 years that this has received full recognition, and even now large-scale coal-dust explosions are arranged at Eskmeals from time to time by the Mines Department to convince possible doubters.

Methane is inflammable between 5·6 and 14·8 per cent in air.† In mixtures both weaker and richer than these there may be burning around the source of ignition, but there is no sustained explosion wave or marked rise of pressure. In the case of coal dust there is a wide variation in the mass of dust required to transmit an explosion, but the cloud must always be dense. It depends in the first place on the fineness of the dust and on the ratio of the combustible to the non-combustible components. If 50 per cent of stone

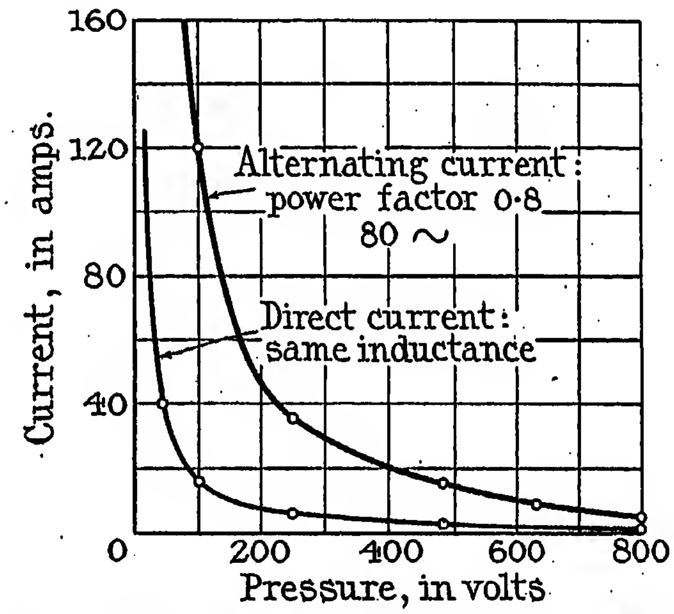


Fig. 1.—Least currents for ignition of coal dust by transient arcs.

dust is added it usually, though not with every kind of coal dust, prevents the transmission of flame. With any dense cloud of dust the presence of 2 per cent of gas makes a coal-dust explosion inevitable.‡ This is the real danger in coal mining; dust with a little gas forms a most dangerous mixture and for this reason haulage is not permitted in return air-ways where the combination is likely to occur. The rise of inflammability is regular from zero to the maximum, as shown in Table 1.

Coal dust can be ignited without the presence of gas by blown-out shots and by electric flashes, provided that there is a dense cloud formed before the arc is struck. Heise and Theim stated § that single electric arcs could not fire coal dust, but this is not the case.

* Report of the Departmental Committee on "The Use of Electricity in Mines" [1904]. Evidence and Index separate.

† Report of the Departmental Committee on the working of the existing special rules for the use of electricity in mines, with appendixes giving the rules as revised by the Committee and a list of fatal accidents (1905–1910) due to the use of electricity in coal mines [1911].

‡ Report of the Inquiry into the Senghenydd Colliery explosion [1913].

* W. Galloway: "On the Influence of Coal-dust in Colliery Explosions," *Proceedings of the Royal Society*, 1884, vol. 37, p. 42.

† R. V. Wheeler: "The Uniform Movement of Flames in Methane-Air Mixtures," *Journal of the Chemical Society*, 1914, vol. 105, p. 2606.

‡ W. M. Thornton: "The Influence of the Presence of Gas on the Inflammability of Coal Dust in Air." Paper read before the British Association, 1913; also see *Colliery Guardian*, 19th September, 1913.

§ F. Heise and Dr. Theim: "Versuche betreffend die Entzündlichkeit von Schlagwettergemischen und Kohlenstoffwirkungen durch die Wirkungen der Electricität," *Glückauf*, 1898, vol. 34, pp. 1, 25 and 45.

The limits* given in Fig. 1 are quite clearly marked and show that such an ignition is well within possibility, though the risk is remote in modern practice. It will be observed that ignition by alternating-current arcs is

TABLE 1.

Direct-current Non-inductive Circuit: 480 *volts,* 3·5 *amperes.*

Percentage of methane in air, by volume	Percentage of full dust explosions
0·0	7·0
0·25	10·0
0·50	17·0
0·75	31·0
1·0	53·0
1·25	75·0
1·50	97·0

more difficult than by direct-current arcs. At 1 000 volts they are much the same on account of the longer arcs at break.

(3) Ignition by Electrostatic Discharge and Friction.

Ignition of coal dust by single condenser discharge sparks has not so far been obtained; nor does it appear probable, for the progress of dust ignition is by a process of disintegration and combustion under the influence of heat and for this a longer time is necessary than the duration of a condenser discharge. It becomes, then, a question of how firedamp can be ignited by such a spark, for there are many conditions of mining which give rise to static discharge in dry atmospheres. Belts, especially those of rubber composition, when rapidly strained and released are subject to this form of electrification, but I have never succeeded in lighting a stream of gas by the long, thin sparks from such a belt. Another very active source of electrification is the formation of dust clouds. Rudge † has shown the potential induced by this to reach thousands of volts, but the surfaces electrified by friction and separation are too small for united discharge to occur in the dust, and only on the colossal scale of dust storms in nature is there sufficient electrification of neighbouring conductors such as clouds to permit spark discharge. Rudge has not succeeded in causing ignition of gas in this way, but it is conceivable that the intense electrification always present in a sudden dust cloud may help the transmission of flame, though experiments that I have made show that an external electric field has no measurable influence on a gas explosion.

A phenomenon of regular occurrence which I was once asked to investigate is the production of long, powerful, sparks at the nozzle of an hydraulic jet filling cement grout into stone packing. This is an example of electrification produced by splashing similar to that of waterfalls and waves, and can be observed by directing a powerful jet of water alone against a surface at short range in the dark. A luminous blue disc will be seen where the jet strikes.

A common instance is the luminous patch where the condenser circulating water outflow of a ship strikes the sea. In the mining case the electrification produced is conducted back through the liquid to the nozzle and the spiral wire support of the rubber feeding tube, and, although gloves are provided, sparks of several inches in length have been known to pass to the body of the worker, with very unpleasant though not dangerous shock. The remedy is to earth the wiring of the supply pipe. In this case also it is unlikely that ignition of firedamp would occur. The activity *per unit length* of the spark is insufficient to start self-ignition of the gas.

The so-called sparks given off at a grindstone are particles of incandescent iron and silica. In spite of their fiery appearance they are singularly inert, but they can ignite pit gas, as also can the sparks from a stone block rubbing on stone. On the merely thermal view of ignition this depends only upon the temperature of the particles; on the ionic view there is the well-known electronic discharge from heated silica to be considered.

Occasional reports are received from coal-cutter operators that a blue flame has been seen to flash around the back of the cut. This may possibly be ignition of minute blowers of gas by hot particles or spots on the cutter tools. It has nothing to do with the electricity supplied to the machine.

A possible source of ignition is electrification by crushing or shear of rock faces, a well-known phenomenon in splitting crystals, which has been observed on a large scale underground when masses of stone are brought down.* This was at one time a favourite explanation of pit explosions, but it is extremely difficult to fire pit gas in this way experimentally. Trials on a larger scale than are possible in a laboratory are necessary to prove electrification by splitting to be a possible source of ignition.

So far the electrical sparks discussed have nothing to do with the use of electricity in mines, except that they illustrate electrical ignition, but sparks occasionally pass between the rotor and stator of induction motors in belt-driven haulages. By their appearance they are static discharges and are caused either by surges on the high-tension system, in which case a spark would be followed by a "power current" and this is never observed, or by electrostatic charge from the belt passing by the shaft to the rotor and escaping by discharge across the narrow air-gap rather than by breaking down the oil film of the bearings. To prevent this the rotor, as well as the stator frame, must be earthed. It is not very likely that these sparks would fire gas if present in the right proportions, but such machines are not now placed where 6 per cent of gas can accumulate, and would be totally enclosed and flame-proof for use inbye.

I have shown elsewhere † that a short spark having an energy of 0·03 joule will just ignite pit gas.

* W. M. Thornton and E. Bowden: "The Ignition of Coal Dust by Single Electric Flashes," *Transactions of the Institution of Mining Engineers,* 1910, vol. 39, pt. 2, p. 1.

† W. A. D. Rudge: "Electrification Produced during the Raising of a Cloud of Dust," *Proceedings of the Royal Society,* 1914, ser. A, vol. 90, p. 256.

* See Report of the Prussian Firedamp Commission of 1881, par. 97.

† "The Ignition of Gases by Condenser Discharge Sparks," *Proceedings of the Royal Society,* 1914, ser. A, vol. 91, p. 17.

This corresponds to the discharge of a condenser having two plates about 40 cm^2 area at a distance apart of 3 mm and charged to 10 000 volts. Areas as small as this can certainly be discharged without ignition, and this indicates that it is not the total energy which is important but the energy per unit length of the spark, in so far as it is a question of energy as distinct from "activation" of the gas by the voltage gradient.

(4) Signalling Bells.

The sparks previously considered are disruptive, that is, they are formed by the process of ionization by collision under the influence of a high voltage gradient across an air-gap. Those now to be examined are break sparks or transient arcs formed at the point where a current-carrying circuit is broken. There are three such circuits to be considered, each with special characteristics, i.e. for signalling, lighting and power. The first is highly inductive, the second usually non-inductive, the third much higher in voltage and with some inductance. The definition of a non-inductive circuit taken here is one the time-constant of which is about 1/1 000th of a second, corresponding, on an alternating current at a frequency of 50, to a power factor of 0·95.

The direct-current signalling bell used in mines is an improved form of the ordinary trembler bell with magnetically operated make and break. Sparking occurs both at the point from which the signal is made (either by means of a push switch or by bringing together bare galvanized-iron wires running along the timbers of a road), and at the trembler contact. Before the signalling bell received special attention both of these could cause ignition. In my earlier work an electric bell was regularly used as the source of ignition when illustrating the effect of broad flanges extinguishing flame. It was this, in fact, that directed attention to the possibility of such an effect occurring in coal mines, and led to the introduction of the first safety bell.* Experiments on break sparks had shown that the essential feature in ignition is some form of ionization. The formation of an arc, as distinct from intense glow discharge or a spark, is only possible when there is a free discharge of electrons from that pole which is for the instant the cathode under the influence of heat. True thermionic discharge precedes an arc and is started by the heat set up in the high-resistance film of gas or metal vapour at the point of separation. There may be heating at a bad contact, but an arc cannot be drawn out unless there is a free thermionic discharge of electrons. The ionization in the arc is maintained by the collision of electrons with molecules and by the collision of charged with uncharged molecules under the intense voltage gradient. The voltage across the break is therefore the most important feature of an arc as a source of activation of the gas in which it is formed. On this view it was only necessary to suppress the inductance voltage at a break in order to minimize the risk of ignition from a bell, and the direct way to do this is to connect across the ends of the magnet winding a non-inductive resistance of value sufficiently low to act as an efficient shunt, but as high as possible to lessen the demand on the signalling battery while the bell is in action. The magnitude of this depends on the inductance of the windings, but resistances as high as 20 times that of the coils were on occasion effective. Between 10 and 20 times is usual.

So long as the pressure across the trembler contact does not exceed about 25 volts, a bell can be made to ring freely in the most explosive mixture of illuminating gas and air—much more sensitive to ignition than firedamp—without igniting it. Pressures of 150 volts across the trembler break are not unusual in an ordinary 2-volt bell. Unless the inductance voltage is suppressed, a bell becomes a miniature magneto so far as regards its power of ignition. The oscillograms of Fig. 2 show how much the voltage is suppressed in a working bell by shunting the magnet windings.

Other means of checking the rise of voltage at break are the use of a short-circuited parallel winding or by copper sleeves over the magnet core.* These delay the change of magnetism, while the shunt diverts the voltage produced by it. Modern direct-current bells can be specified so that inflammable gas shall not be ignited by the spark at the trembler contact. Bells for alternating-current circuits have usually no make and break, but work with a magnetically operated oscillating armature. They have a highly inductive winding and the spark at the signalling point where the circuit is made and broken is dangerous. It can be suppressed by arranging a high resistance across the wires so that it is brought into action by a double contact when the signal is made. Many bells have now, in addition to the electrical safety devices mentioned, mechanical protection by flame-proof enclosure.

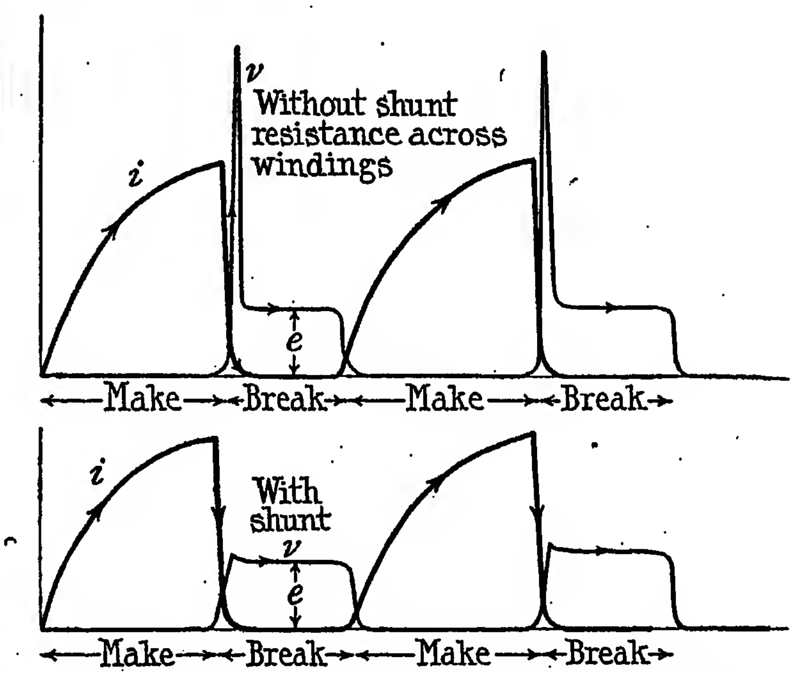


Fig. 2.—Oscillograms of signalling-bell currents, and voltage across trembler contact.

(5) Shot-firing Generators.

The alternating-current hand generators by which detonators for shot-firing are exploded are of two types, high and low tension, giving voltages of 150 and 1·5

* W. M. Thornton: "A New Battery Signalling Bell," *Transactions of the Institution of Mining Engineers*, 1915, vol. 50, pt. 1, p. 19.

* R. V. Wheeler and W. M. Thornton: Home Office Report on "Electric Signalling with Bare Wires so far as regards the Danger of Ignition of Inflammable Gaseous Mixtures by the Break Spark at the Signal Wires" [1916].

on load respectively. The difference between a good and bad generator may depend only upon their voltages. A common method of testing whether a generator is in good working order before a shot is fired is to touch the ends of the leads together and observe the nature of the spark. Since many thousands of shots are fired in a day in the British Isles alone, it is important to know whether there is even the remotest possibility of ignition of firedamp by these testing sparks. Four out of five of such machines will, I find, ignite a 9·5 per cent mixture of methane and air, generally after many trials. Since, however, before a shot is fired the place must be declared free from gas, the risk of testing the circuit by open sparking is less dangerous than the risk of having uncertain shot-firing. Where it is thought necessary, a small closed tube with a flexible make-and-break contact inside is a safe means of examining the spark.

(6) Lamps, and Ignition by Hot Wires.

Electric lighting in coal mines is passing through two phases, the displacement of the portable oil lamp on account of its poor light and possible risk of ignition by breakage, and the improvement of general lighting not only at shaft landings but also along the roads. The economic value of the former change is now recognized, and for the latter there is no reason why the working roads of a mine should not be as well lighted as those above ground if by doing so an economic advantage can be proved in safety and rapidity of handling haulages. Stress is laid here on the economics of the question, for unless it can be shown by trial that immunity from accident and rapidity of transport are obtained, there is no reason to change the present state of affairs.

From the point of view of safety, lighting circuits differ only from power circuits in the vulnerability of the lamp. Thanks to the severe conditions of running, the filaments of such lamps as motor-car headlights are as robust as can be desired. Experiments made by the United States Bureau of Mines have shown that hot-wire lamps with short, thick filaments are relatively more dangerous than those with finer wires,* as previously shown for carbon lamps. The voltage on portable lamps is limited by the weight which can be carried, but the future of fixed road lamps might well be in the direction of running them at the signalling voltage, 25, permitted everywhere inbye, and using standard car lamps, protected from mechanical damage by the usual glass and metal shades. If the voltage is raised much above 25 a new condition enters. There is for all conductors a minimum arcing voltage. The spark at break of a 100-volt, 16 candle-power carbon filament will fire gas if the broken ends remain in fizzling contact. That at 25 volts will not, as the arc cannot persist. There is again a remarkable difference between direct- and alternating-current breaks as a source of ignition which will be considered later. Ignition arising from broken lamps is regarded chiefly from the risk of contact of gas with the hot, unbroken filament. The general problem of ignition by hot wires has been worked out experimentally* and the following conclusions have been reached. Ignition of hydrogen mixtures, taken as the most sensitive, begins with most metals at a temperature well below red heat, at that in fact at which thermionic emission from the wire is first observed, i.e. about 200° C. It always begins by surface combustion, the heat from which may fire the rest of the mixture or may be dissipated by radiation so rapidly that self-ignition does not occur. The least igniting current is a linear function of the diameter of the wire. Methane can only be ignited by any hot wire below a temperature of about 1 800° C. when a current of gas is swept over the wire. With platinum wires 0·01 cm in diameter over 2 amperes are required to reach ignition conditions, and as often as not the wire melts without firing the gas if the circuit voltage is low. With tungsten wires there is no difference between the igniting currents of hydrogen, methane, carbon monoxide or coal gas, and the wire is always red hot before ignition of the mixtures occurs. The igniting current is independent of the proportion of inflammable gas in the mixture in the case of all the paraffins, and is independent of total gas pressure down to one-third of an atmosphere or up to seven atmospheres. Electric or magnetic fields have no influence on hot-wire ignition. Ignition by tungsten wires below 0·2 mm diameter is more difficult than with any other metal—a fact of importance in mining, since no greater safety could be obtained by the use of filaments of other metals than that now commonly employed.

A recent decision of the United States Bureau of Mines makes it necessary to provide some automatic means of cutting off the current in a hot-wire vacuum lamp as soon as the glass is cracked so that an inflammable mixture may enter. One method of doing this consists of a pneumatic collapsible chamber which operates a small switch contact when air is admitted to the lamp. The smallest pressure at which it will operate is about 1/25th of an atmosphere, more usually about 1/10th. Firedamp is not inflammable by hot wires at pressures below one-third of an atmosphere. There is here a very fair margin of safety.

A simpler and safer plan than trusting to safety cut-out devices in lamps when broken, is to provide an indicator on each lamp, either electric or oil-burning, to give a danger signal to the worker when a dangerous proportion of gas is present, so that he may withdraw from the place until the ventilation copes with the inrush of gas.

(7) Ignition by Break of Circuit.

A complete break of cable is very rare in coal mining. A fall of stone may force the conductors into contact with one another or the sheath or armouring. In such a case protective cut-out gear operates. In order to ascertain whether there could be a dangerous flash from an unarmoured lead-sheathed, three-phase cable cut into by a fall, the following trial was arranged with the co-operation of the Newcastle Electric Supply Co., Messrs. Reyrolle & Co., and the Metropolitan-Vickers Co.

A 20-ft. length of 3 000-volt, three-phase, paper-

* H. H. Clark and L. C. Ilsley: "The Ignition of Mine Gases by the Filaments of Incandescent Lamps" (Bureau of Mines, Washington, Technical Paper No. 52).

* W. M. Thornton: "The Ignition of Gase by Hot Wires," *Philosophical Magazine*, 1919, ser. 6 vol. 38, p. 613.

insulated, lead-sheathed cable was sealed at one end and connected at the other through a 50-ampere oil switch to a 200-kVA transformer, and through it to the 5 000-volt busbars of a large substation fed direct from Carville. The cable was placed on a concrete floor beneath a platform some 4 ft. high, and a steel wedge was laid on it in such a way that a stone weighing about 1 cwt. dropped from the platform should strike it fairly. The object of the test was to see whether a flash could be observed to issue from the cable at the point and moment of damage. Two observers were stationed close to the spot, and though the conductors were cut well into by the fall, no external flash was seen. The trip-gear operated quickly enough to prevent any sign of burning at the point of short-circuit.

On two occasions at West Stanley and Auckland Park, where cables had been short-circuited by falls and ignition suspected, no sign of external flame or

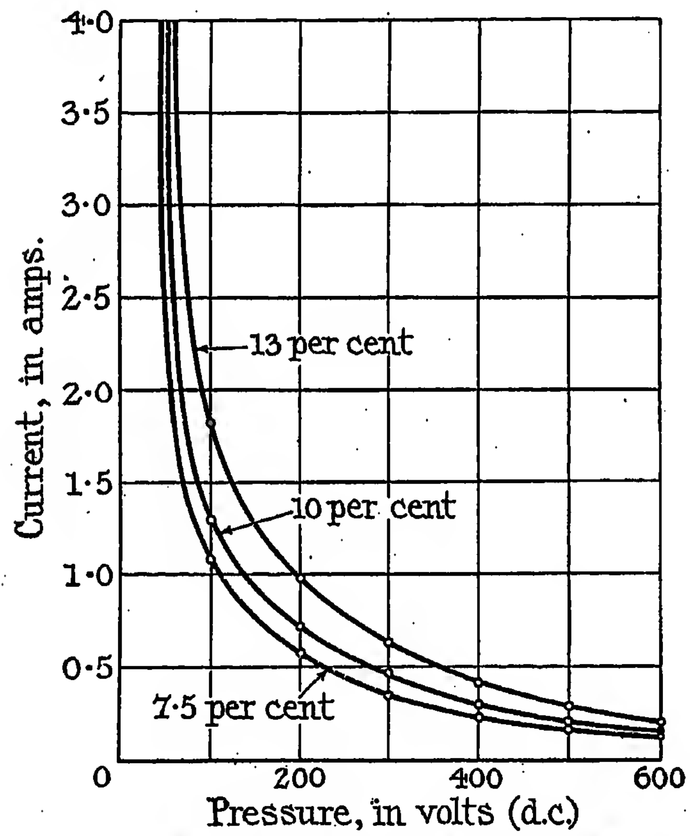


FIG. 3.—Least igniting currents of methane-air mixtures by transient arcs.

even break was found. From these and many other practical tests it may be concluded that with modern armoured cables the risk of open sparking due to the damage of a cable by a fall is slight, and the further condition that there should be at the same moment a mixture of firedamp and air between 5·6 and 14·8 per cent makes the possibility of a local explosion from this cause remote. It is, however, possible that a cable may be drawn out of a junction box by a fall, but the break of circuit will then have taken place within it and the enclosure must be strong enough to deal with the arc until the trip-gear operates. In pulling clear there may be an external break of circuit, and it is therefore necessary to examine the limiting conditions of ignition by break arcs with both direct and alternating current.*

* W. M. THORNTON: "The Electrical Ignition of Gaseous Mixtures," *Proceedings of the Royal Society*, A, 1914, vol. 90, p. 272.

(i) *Direct current.*

(*a*) *Influence of voltage.*—There is for every gaseous mixture a sharply defined current which just causes ignition when broken in it. Fig. 3 gives for pure methane the range of variation of the least igniting current with voltage when iron poles are used to resemble armouring. The curves have a mean equation $(V - 15)/(I - 0\cdot 11) = 10\cdot 5$. Below 15 volts ignition by break of a non-inductive circuit is extremely difficult if not impossible, and at high voltages a current of about 0·1 ampere is sufficient. The lower voltage is below arcing potential; at the higher a transient arc becomes a spark characterized by ionization by collision in the field across the break.

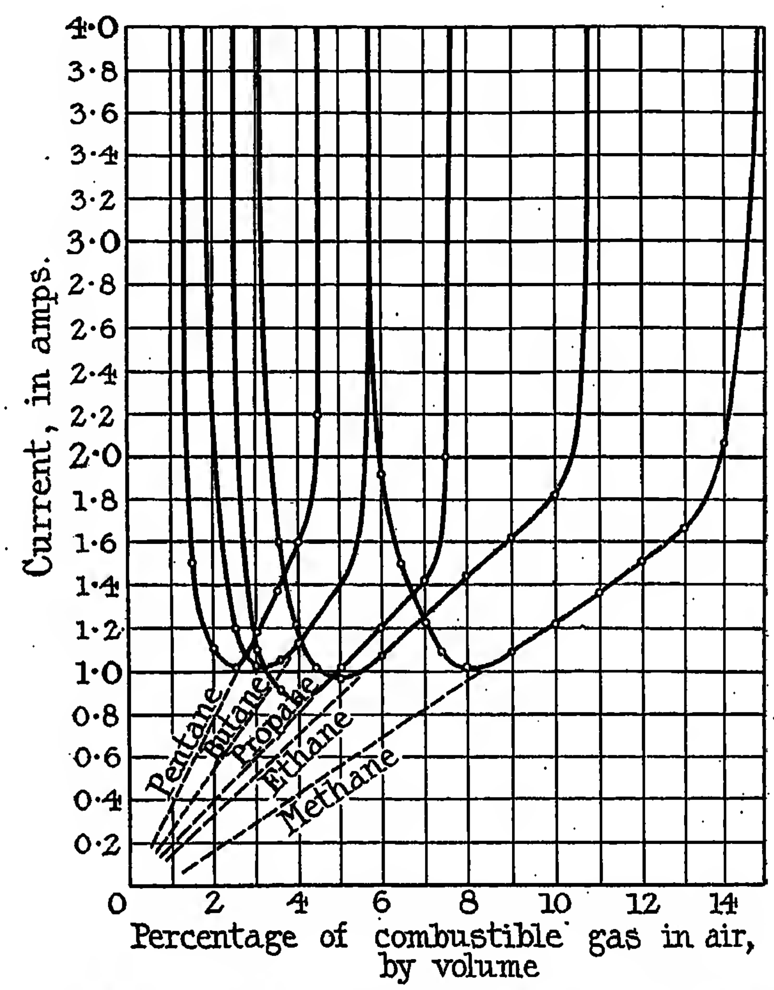


FIG. 4.—Influence of proportion of gas in air on least igniting direct currents.

(*b*) *Influence of proportion of gas in mixture.*—The characteristic phenomena of ignition by direct currents are well illustrated by the curves given in Fig. 4.

Mixtures of firedamp and air are most easily ignited at 8 per cent and, though this is a point of less practical importance in this country, all the paraffins have the same least igniting current in their most sensitive mixtures. The physical and chemical meaning of this has been discussed elsewhere.

(ii) *Alternating current.*

(*a*) *Influence of voltage.*—The essential feature of ignition by alternating-current break sparks is the remarkable influence of frequency at different voltages. The curves of Fig. 5 illustrate this. Thus at 500 volts a direct current of 0·2 ampere will cause ignition, quite possible in a badly earthed armouring with a fault developing, but at the same voltage and a frequency of

100, 11 amperes are necessary, other things being the same, a ratio of 55 to 1 in favour of high-frequency alternating current. At 50 periods it is about half this—quite worth having.

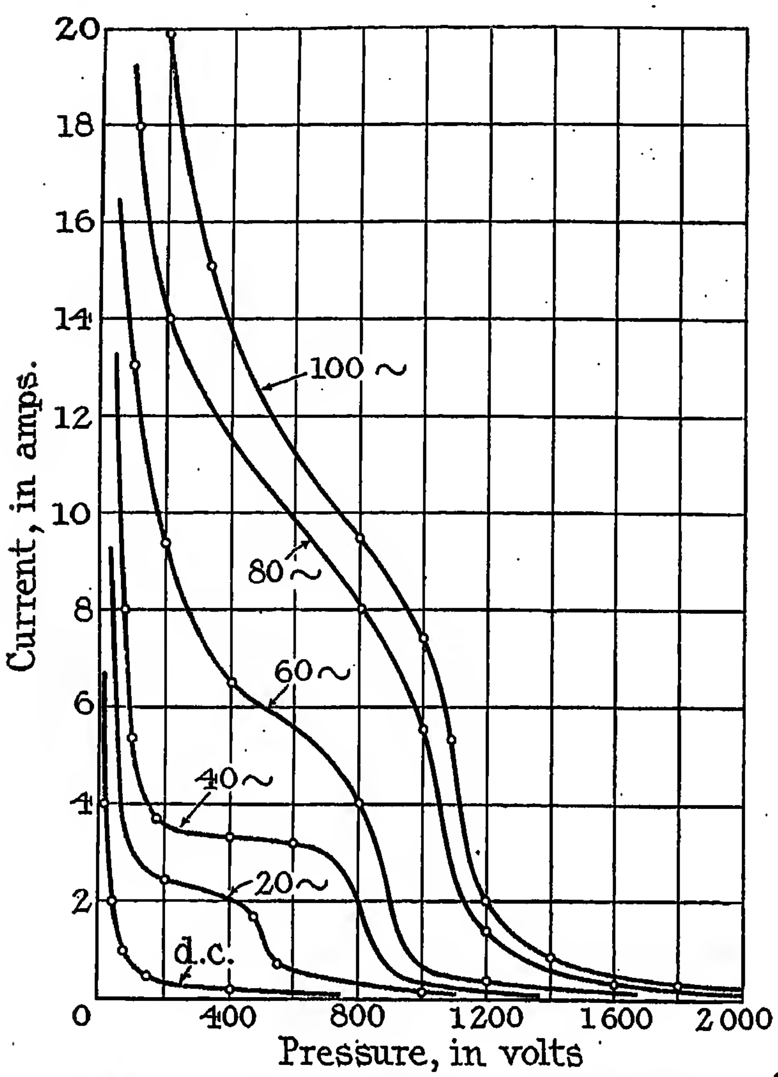


FIG. 5.—Influence of frequency on the ignition of methane by transient arcs, at various voltages.

(*b*) *Influence of proportion of gas.*—Remarkable as the above curves are, they are perhaps less striking than those of Fig. 6. The curves are a set of parabolas symmetrical between the limits of inflammability, so that the most easily ignited mixture is midway between them (see Table 2).

value are most difficult to ignite; a fact that calls for explanation by those who support the thermal theory of ignition.

(*c*) *Influence of frequency, the voltage being constant.*—A recent examination of the influence of frequency up to 500 periods shows the complex nature of the physical changes in the act of ignition. Fig. 7 is for pure methane in a 9·5 per cent mixture ignited by the break of a non-inductive circuit maintained at 200 volts.

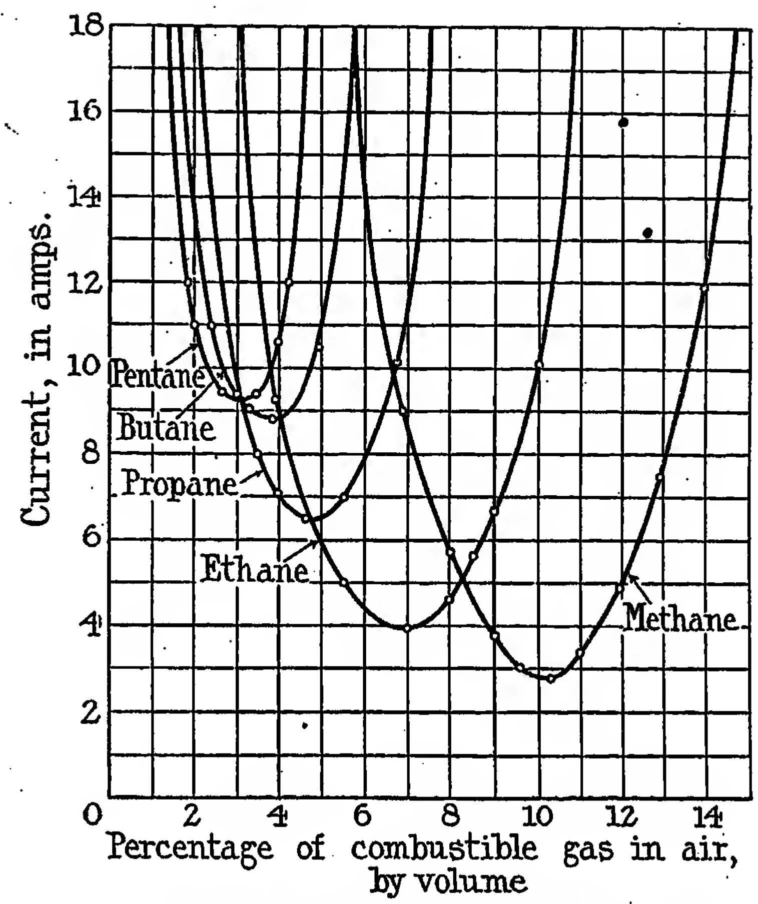


FIG. 6.—Influence of proportion of gas on least igniting alternating currents.

The first point to be observed is the high values of the currents necessary. After an initial delay the curve begins to rise as if logarithmic. There is an apparent time-constant, the meaning of which gives the reason for the curve. Writing the equation for the latter in the form $i = I(1 - \epsilon^{-f/c})$ the critical constant is clearly a frequency, and by the usual method of determining time-constants this is found to be about 110. What is there about an arc that can have such a critical time-relation? A transient alternating-current arc differs only from a direct-current arc in the fact that

TABLE 2.

Gas	Limits of inflammability		Mean	Observed minimum	Combustion to CO_2 at	Combustion to CO at	Mean of these
	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
Methane ..	5·6	14·8	10·2	10·2	9·4	12·0	10·7
Ethane ..	3·1	10·7	6·90	6·90	5·5	7·7	6·6
Propane ..	2·17	7·35	4·76	4·80	3·96	6·0	4·98
Butane ..	1·65	5·7	3·67	3·75	3·07	4·38	3·72
Pentane ..	1·35	4·5	2·92	3·05	2·51	3·61	3·06

The practical bearing of this is that when alternating currents are used there is much less risk of ignition of the weaker mixtures. The most sensitive point is 2 per cent higher than in Fig. 4.

One notable feature is that gases of greatest calorific

each pole is alternately anode and cathode and is heated and cooled as the current rises and falls. Since the maintenance of an arc depends in the first place upon the stream of electrons from the cathode,* such a relation must mean that when the frequency reaches a critical value the poles remain hot enough to give a continuous thermionic discharge while the current falls to zero, facilitating the activation of the gas in contact with the poles and improving ignition. For it is clear that ignition is relatively easier at high frequencies in the sense that the rate of rise is then less. If the early rate had been maintained it would have been impossible to ignite firedamp at frequencies of 500 except by the break of circuit of a machine of some 250 kW working at full load on unity power factor. There is at a frequency of 165 p.p.s. in the case of methane, but rather higher in coal gas, a most singular increase in ease of ignition. This is not maintained, for at a frequency approaching 400 the curve reverts to its earlier type.

The heating of the cathode or negative pole is greatest

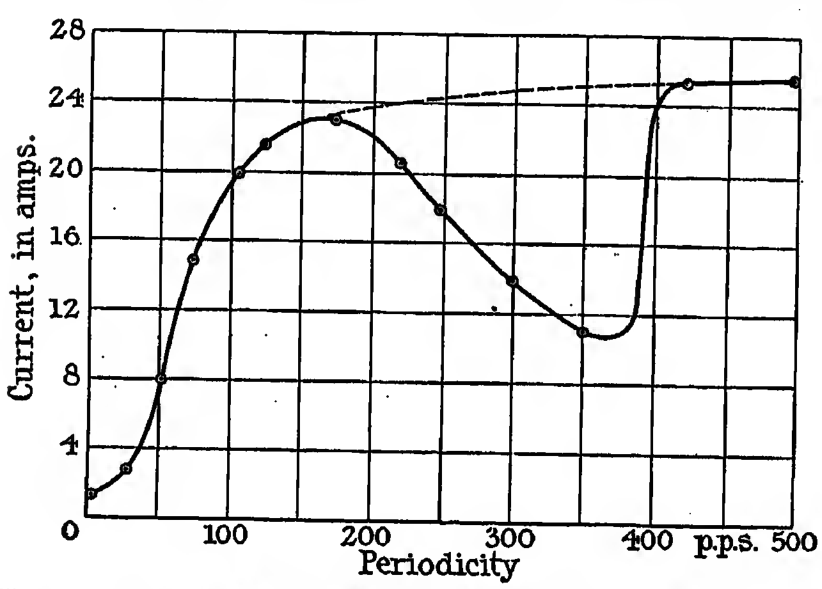


FIG. 7.—Influence of higher frequencies on ignition of methane. Transient arcs at 200 volts.

when the current is unidirectional, and the smallest igniting currents are therefore found in that case. As the frequency is raised, the difficulty of striking an arc increases on account of the delay in making a hot spot from which thermionic emission can take place. Now it is found that at the 200 volts used, and with the relatively small currents, there is never any "overshoot." Wherever in a half cycle the current is broken, it falls to zero and stops. During this fall the fresh gas mixture rushes into the space occupied by the arc, and ignition can occur if it is long enough in contact with arc and hot metal to be activated. The higher the frequency the shorter the duration of contact and therefore the higher the current necessary to obtain the result in the time. It will be clear that at some frequency the pole will continue to glow and give off electrons after the arc is extinguished for so long that ignition can occur even though the arc itself does not last long enough for that purpose. In addition, if ignition is ionic rather than thermal—as everything indicates—the more rapid removal of the arc may make ignition easier by bringing the gas more quickly into contact with a hot surface still emitting electrons. There can be no doubt that the rate of liberation of electrons from the cathode in air is much greater than that from the surface of the arc itself, for if the latter were greater the arc in air would expand in volume, like an explosion, by continually enlarging its conducting path. At still higher frequencies the heat given to the pole while the arc lasts is insufficient to raise more than a minute part of the surface to emission temperature. Heat is conducted from this so quickly that hot-spot ignition can no longer occur. There are few phenomena more striking than the suddenness with which thermionic emission ceases when there is a small drop of temperature from a critical value,* and the reversion of the curve of Fig. 7 to the original type at a frequency of about 380 is, I take it, an illustration of this.

Other gases have been examined, but the dip in the curve is most marked in the case of methane. Fig. 8 shows the variation in illuminating gas both when the poles are of iron and of nickel. The presence of hydrogen raises the depression and makes it a straight line.

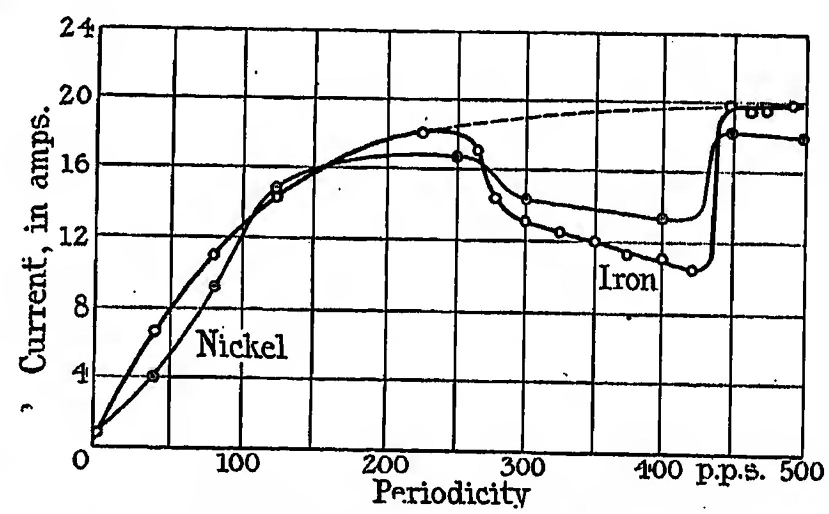


FIG. 8.—Ignition of illuminating gas at various frequencies and 200 volts.

The statement has been made here that ignition is electrical rather than thermal. As a test of this in the case of break sparks the following experiment was made. The least igniting current of a 35 per cent hydrogen-in-air mixture was found by trial at 200 volts, 250 p.p.s. to be 0·4 ampere. The same poles were than sparked in pure hydrogen to remove oxide or occluded oxygen, and it was then found that the explosive mixture could not be ignited with less than 6 amperes broken. The sparks were large and bright but were electrically inert though their thermal value was many times greater than before. The first step in ignition is the formation of active oxygen ions. There is direct evidence for this in the phenomena of ignition by condenser discharge. There is no difference between hydrogen and other gases except in sensitiveness to spark ignition.

The conclusion to be drawn from these determinations of the safety limits is that alternating current is always safer than direct current when there is little inductance, but that with the voltages and currents in use there is no

* MAURICE LEBLANC (fils): "L'arc Électrique," p. 22, par. 14.

* O. W. RICHARDSON: "The Emission of Electricity from Hot Bodies," p. 52, Fig. 8.

real security for power circuits of either kind, except by complete enclosure. The currents in lighting and signalling circuits can, however, be kept well within the limits of safety so far as a break is concerned, and ignition by the hot filament of a lamp, always so difficult in methane, can also be prevented by some device which breaks the circuit when the lamp is cracked.

(8) Improved Lighting in Coal Mines.

(*a*) *Main roads.*—The results just described provide a means of improving the lighting of coal mines and at the same time increasing the safety of working. At a frequency of 150 p.p.s. the least current for ignition from a lighting circuit is 23·5 amperes at 200 volts. The least direct current at this voltage is 0·4 ampere. The ratio of these is 60 to 1, which should commend alter-

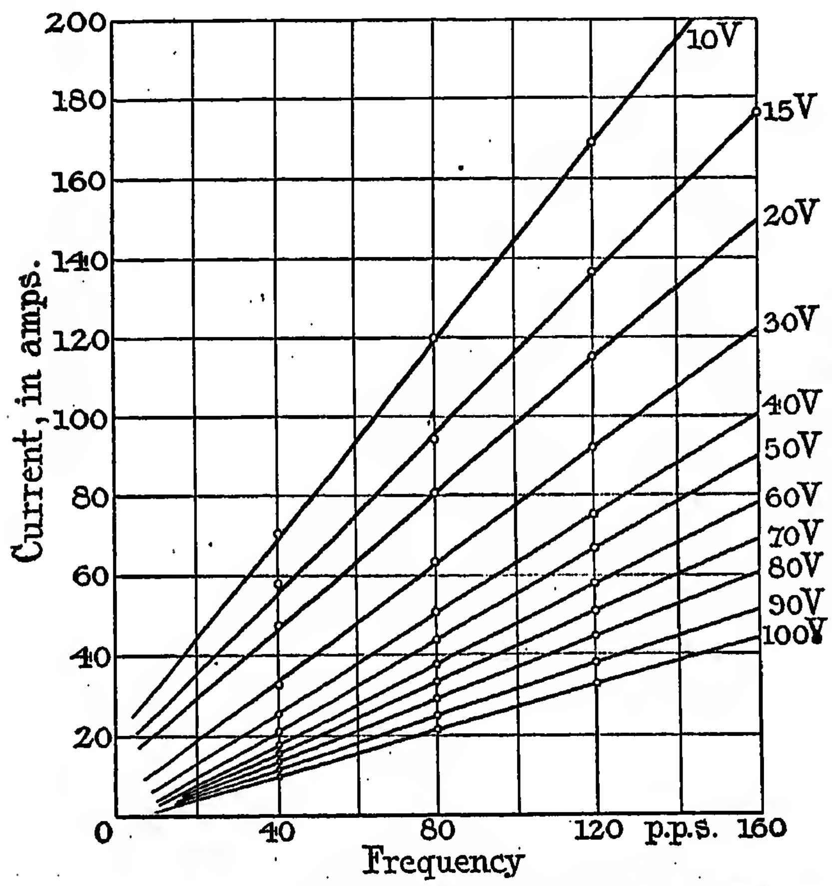


Fig. 9.—Ignition of methane by low-voltage transient arcs at various frequencies.

nating current to those who desire "safety first" in lighting. But there is no necessity to run lighting leads at this voltage, a voltage of 25 being, as previously stated, permitted everywhere. When we come to examine the currents necessary to ignite firedamp from such low-voltage circuits, the results of Fig. 9 are obtained. At 160 periods and 15 volts not less than 175 amperes would fire the most explosive mixture (10 per cent of firedamp) when broken in it. Lighting and signalling might be operated from the same circuit if desired, and, with the requisite protective gear to keep the maximum current in the case of a combined short-circuit and break to less than 175 amperes, immunity as complete as possible, apart from the human element, is obtained. The inclusion of a resistance of 0·16 ohm, or of a choking coil of similar reactance, would secure this, though the less inductance the better, so far as ignition is concerned. Since there is no risk of shock at this voltage there is no reason why enclosed replaceable fuses should not be used in each lamp fitting and feeder.

(*b*) *At the coal face.*—In order to improve lighting at the working face it is necessary to devise a flexible and safe means of making contact. The following arrangement was devised for this purpose. Each portable lamp is fitted with a plug in its base so that it can be connected in the usual way to a socket of special design attached by flexible "cabtyre" leads to the 25-volt supply or to the power circuit through a transformer. The battery of the portable lamp of this type is smaller than in present lamps, for it has only to supply energy sufficient to give light when travelling to and from the working place. The double-filament lamp is pressed into the socket in which there is a safety interlock, and the contact is then switched over from the 2-volt to the 15- or 25-volt filament. The increase in illumination obtained by this will be evident, but it is doubtful whether so great an increase is desirable, or desired by the miner himself. If it is an economic proposition to increase the lighting at the coal face to ten times its present amount, then here is a means of doing it with a factor of safety greater than that of present practice. The current taken by each lamp would be about 1 ampere, and this at 15 volts is only 0·6 per cent of the clean break igniting current. By the use of these higher-frequency currents and lamps with both internal and external cut-outs it is possible to do for the miner what the Davy lamp did in the old oil lamp and candle days—to give better illumination with greater safety than is even now possible.

(9) Electrical Oscillations on Cables Sheaths and Conductors.

The experiments recently made at Ashington on wireless communication with places underground is a revival of those made by Mr. A. W. Heaviside many years ago in the same district, and brings forward again the possibility of risk from oscillations on cable sheaths, and sparking to earth at points of high potential. I examined this some years ago and found that electrical oscillations on the conductors within an insulated lead sheath due to switching or surges did not give rise to high-voltage oscillations on the sheath, nor any sparking at the ends where the potential-rise might be expected to be greatest. In the case of cable armouring it may be possible to obtain minute sparks, for the surge impedance of such a conductor is higher than that of a plain tube, on account of the twist of the wires. The passage of electrical oscillations along a corrugated surface such as the longitudinal section of a cable has not been investigated mathematically. The impedance of such a path might be great. There is, however, a real danger in the case of an unenclosed circuit in which there is heavy inductance, a voltage transformer for example. A surge on such a system reaching a coil has been known to give rise to a spark to adjacent conductors by which gas might be fired, and in one case such a surge has been suspected of causing an explosion in the cubicle of an oil switch underground. The gases given off by heavy switching are a mixture of hydrogen and methane, the products of dissociation of the oil by the arc. The presence of hydrogen extends the range of inflammability

of "switch gas" and air, for it alone is inflammable in mixtures from 6 to 72 per cent. For the safety of coal mining two things are necessary: (i) The space above the oil must be thoroughly ventilated so that the gas is conveyed clear of the cubicle, and the switch so constructed that even if the enclosed gas is ignited no flame can emerge; and (ii) all live conductors should be enclosed so that there is a continuous bond between the armouring and the switch-box metal. To prevent the possibility of a surge spark through air the space must be filled with compound.

(10) Electrical Endosmose and Faults.

For everything except haulages in which fine speed-control is necessary, alternating current is preferred to direct current. From the point of view of incidental safety the advantage is with alternating current, not only on account of the lower risks of ignition previously discussed but also on account of the relative freedom from faults. It is impossible in a mine to avoid having cables in contact with moisture in some place or another. Direct-current systems are often subject to trouble in damp places. There is a mechanical pressure of electrical endosmose by which an incipient fault is always augmented. "Electricity only moves electricity," and the motion is clearly ionic. Water is carried down an electric field from positive to negative pole. Mr. Evershed demonstrated this excellently in his paper * read in 1913. If an alternating field is applied, the amplitude of the movement can be observed under the microscope. At a frequency of 80 p.p.s. it is about $0 \cdot 0003$ cm in a thin film of water. An approximate estimate of the pressure may be made as follows. Assume the whole action to be electrical and consider a single molecule to be carrying a unit ionic charge e. The value of this is $1 \cdot 57 \times 10^{-20}$ electromagnetic units. The force on such an ion in a field of 5 000 V/cm (a not unlikely value in the dielectric) is He dynes, where H is the field in absolute electromagnetic units, here $5\,000 \times 10^8$. Thus $He = 5\,000 \times 10^8 \times 1 \cdot 57 \times 10^{-20} = 7 \cdot 85 \times 10^{-9}$. The diameter of a water molecule is about 4×10^{-8} cm and its cross-sectional area $12 \cdot 56 \times 10^{-16}$ cm^2. The force on this area alone is $(7 \cdot 85 \times 10^{-9})/(12 \cdot 56 \times 10^{-16}) = 6 \cdot 25 \times 10^6$ dynes/cm^2, i.e. 14 lb./cm^2 or 90 lb./sq. in., a quite considerable pressure forcing moisture into the fault. It is less than this on account of the space factor of molecules in a liquid, but not much. The number of molecules, N, in a gramme molecule of gas is about 7×10^{23}. The molecular weight of water being 18 there are 4×10^{22} molecules in a gramme of gas or liquid. Taking each molecule of water as $3 \cdot 5 \times 10^{-8}$ cm diameter (its lowest estimate), its volume, v, is $2 \cdot 25 \times 10^{-23}$. The product Nv is $0 \cdot 9$ cm^3, and, since a gramme of water at 15° C. has a volume of 1 cm^3, the space factor is $0 \cdot 9$.

The well-known Hebburn case, in which the number of small cable faults was reduced from 164 to 1 in 6 years by changing over from direct to alternating current, is the most remarkable example of the above effect, and of the further valuable fact that a faulty cable dries itself out when the supply is alternating.

* "The Characteristics of Insulation Resistance," *Journal I.E.E.*, 1914, vol. 52, p. 51.

(11) Earthing.

One of the difficulties in mining is the provision of an efficient earth underground in order to avoid electric shock, and, since coal is not a conductor but a very good insulator, a leakage to earth on an underground network cannot as a rule return to the earth plate at the surface without the risk of a large potential gradient somewhere underground. This is one reason why a continuous bonding of armouring to bank is specified in the special rules, in order to avoid shock by leakage. It is not too much to say that on the provision of an efficient earth the whole safety of electricity in mining depends. There are two types of earth plate in general use, viz. a tube driven vertically into the ground, and a flat plate also vertical. The essential feature of a good earth is to get the lines of leakage flow to diverge as quickly as possible from as large an area as possible, in order that the resistance may be small where the area of flow is small. In the case of a vertical tube the lines of flow

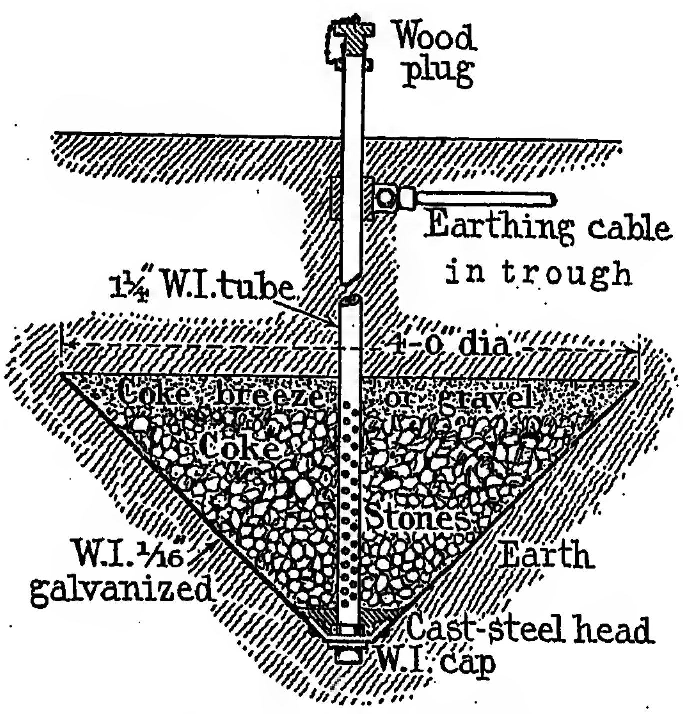


Fig. 10.—Earthing plate.

to another similar earth of opposite polarity at a great distance are at first radial. The voltage gradient is then inversely proportional to the distance from the tube, for if I is the total leakage current per unit length the current density at a distance r is $I/(2\pi r)$, and if the resistivity of the ground is everywhere the same the gradient is $\rho I/(2\pi r)$, a maximum when $r = a$, the radius of the tube.

In the case of a plate the lines diverge to a circle and the gradient near the plate then remains nearly constant for a distance comparable with about half of the width perpendicular to it. The lines of flow from a long, flat, earth plate are hyperbolas and the equipotential lines confocal ellipses becoming, in effect, circles at a radius of about $1\frac{1}{2}$ times the width of the plate. The resistance-drop from such a plate therefore remains high and nearly constant for a much greater distance than that of a tube of the same periphery. For example, take a plate π ft. wide, and the corresponding tube 1 ft. in diameter. At a distance of 3 ft. from the centre of the

plate perpendicular to it, the current density has fallen to rather more than one-half its value at the plate. In the latter at the same distance from the surface it is one-quarter of the surface density, but, since the plate has two surfaces and the tube one, there is practically no difference between them as regards their value as an earth.

With a hemispherical earth plate the lines spreading radially give a gradient inversely proportional to the square of the distance, reaching a maximum of $I/(2\pi a^2)$ at the surface, neglecting any current flowing from the inner side. If this is also active the maximum density is $I/(4\pi a^2)$. Comparing this with a square plate of side b they will have the same current density if $I/(4\pi a^2) = I/(2b^2)$, or $a = b/2\cdot5$. Taking $b = \pi$ ft. square, a is nearly 15 in., and at a distance of 3 ft. from the surface the current density is one-ninth of the maximum value. By keeping the earth moist (and therefore of low resistivity) around the plate the voltage gradient is lowered in the place where it is necessary that it should be low.

Vertical surfaces are difficult to maintain in good contact with surrounding earth. The earth plate shown in Fig. 10 was designed to make its own contact without additional stemming, to give a rapidly diverging flow and so to have low resistance close to the surface, and to provide an underground pool of water from which by diffusion the ground around the plate might be kept moist.

A conical dish of $\frac{1}{16}$-in. galvanized iron is riveted to a cast-steel boss into which is screwed a wrought-iron pipe about 8 ft. long. Holes $\frac{3}{16}$ in. diameter are drilled in the lower part of the pipe, and the bottom of the dish is filled with a pitch cement to avoid leakage. The plate is sunk into the previously moistened ground and filled with broken half-bricks or small stones, covered with gravel and the earth is then returned. Sufficient water is admitted to fill the dish to overflowing, and a fresh supply can be given if the resistance rises in dry weather.

(12) Conclusion.

The researches mentioned in the paper, though they are a small part of the whole ground, will have served to show the variety of the phenomena and the need for an attempt to cover so wide a field. From shock there is now little risk of accident; in signalling circuits there is need for further control in the use of alternating-current bells, but there are many advantages in its use, especially in connection with improved electric lighting below ground. By keeping the leakage trips set low, transient arcs due to break of circuit and armouring may be kept below the limits found here to be dangerous. No other mode of obtaining safety is reliable. Oscillations due to wireless or other surges are not regarded as a serious risk. Alternating current is preferred to direct current on account of its freedom from water faults or endosmose.

Discussion before The Institution, 31 January, 1924.

Mr. C. P. Sparks: I consider that the industry, as a whole, will have good cause to thank the author for his very exhaustive and persistent work over the past 12 or 14 years spent in investigating this subject. On page 481 it is pointed out that safety in coal mines depends on (*a*) efficient ventilation; (*b*) elimination of flame or open sparking; (*c*) improved illumination; and (*d*) training in habits of observation and carefulness —in other words, "safety first." As far as electricity is concerned we have to do with items (*b*) and (*c*) only. In view of the responsibility thrown on the management by the use of electricity, the paper is of a reassuring character, as it enables a considered opinion to be formed as to which class of open sparking is safe and which is dangerous. The use of electricity in mines depends directly on the judgment of the management, the mine manager being held responsible by Act of Parliament and by the Home Office Regulations as to where, when and how he may use electricity. We can only advise the mine owners as to the merits and possible methods of using electricity, but the responsibility for its use rests upon the mine manager, and it is a very serious responsibility. For instance, the Government Regulations contain this definition: "'Open sparking' means sparking which owing to the lack of adequate provisions for preventing the ignition of inflammable gas external to the apparatus would ignite such inflammable gas." The manager and his staff have to decide if there is danger from "open sparking"; if there is, he must not use electricity underground. Regulation 132 commences: "In any part of a mine in which inflammable gas, although not normally present, is likely to occur in quantity sufficient to be indicative of danger, the following additional requirements shall be observed." Then it details the requirements, always with the expression "so that in the normal working thereof there shall be no risk of open sparking." The manager has, therefore, to have a considered idea as to what "open sparking" is and what is safe. Here the present paper is of a reassuring character: it is most helpful to the management to be able to see that, under certain conditions, sparking that appears dangerous (as one spark may look exactly the same as any other) may under the defined conditions of working be safe. The author's investigations show that, far from every visible spark being dangerous, they may be divided into several categories: (1) Those that are safe; (2) those that are risky; and (3) those that are dangerous. The author's investigations show that electric power development in collieries has been fortunate in several respects. While the first development took place with direct current, the advantage of transmission has resulted in the 50-period, three-phase system becoming the general standard. The author shows that direct current is 25 times as dangerous (from the point of view of a spark firing an explosive mixture) as alternating current at 50 periods per second. In this case commercial development has been on the lines of general safety, although the 50-period system was adopted primarily

for other reasons; it was not known in those early days, in fact it has been known only comparatively recently, that it was so much less harmful. The second factor assisting electrical development is the inertness of methane. A third factor (see page 485) shows that the peculiar characteristics of tungsten, which is used for lamp filaments and which was not chosen from the point of view of safety, have given a greater margin of safety than could be obtained with any other metal. The author's experiments, while they indicate what may occur under a combination of circumstances, show that ignition results from combinations which rarely happen. This is emphasized by the long period during which electric signalling bells were in use before they were found to possess dangerous characteristics. I believe that the first electric development in mines was the signal bell some 40–50 years ago, but it was not until 1913 that any suspicion arose with regard to the danger of electric signal bells. In 1913, following the Senghenydd disaster, very careful investigations were made by several people, and in 1916 the author and Dr. Wheeler showed how electric signalling bells could be made absolutely safe. The fact that this hidden danger existed unsuspected for so many years, emphasizes the fact that the risk of danger only occurs under a combination of circumstances. The importance of research is emphasized by the fact that directly research was applied to the characteristics of electric signalling bells they were found to possess an element of danger. Safety in mines has been increased in the past due to improved illumination, and the further improvement in illumination will still further reduce the daily roll of accidents. Again, electric power lightens the burden of work, and the range of seams that can be worked is increased by better illumination and the use of power, thus reducing the cost of winning coal (benefiting both the worker and the public), whilst the use of electric power will result in a great reduction in the number of horses at present employed underground. The author's investigations of the effect of frequency on ignition are of special value as opening up definite possibilities of increasing the standard of illumination not only on the roads but at the face. I see no special difficulty in increasing the frequency of a small proportion of the power from 50 to 150 periods, or even higher, if this gives complete immunity of risk from lighting. While not desiring to throw any doubt on the author's experiments, I feel that, before we can ask the Home Office to modify the existing Regulations to allow the use of a periodicity of 150 for lighting at the face, a further exhaustive series of tests are essential.

Mr. R. Nelson: In that section of the paper headed "Conclusion" the author states (1) that the risk of shock has practically been eliminated, and (2) that by keeping the leakage trips set low there is no risk from transient arcs due to the accidental breaking of an armoured cable. I entirely agree with those two statements. The position in both respects is well established, and from the point of view of safety a great deal of ground has been cleared thereby. It might indeed be asked: What remains? The three things upon which safety in mines chiefly depends are mentioned by the author, viz. efficient ventilation, the elimination of all sources of flame or open sparking, and the improvement of underground illumination. The last alone of the three has not yet been attained, but, as the author justly remarks, it is doubtful whether an increase is really desired (in the sense of being demanded) by the miner himself. Fig. 9 indicates that at a frequency of 50 periods and at a pressure of 50 volts, which is a reasonable voltage for local distribution, something of the order of 25 amperes is required to ignite firedamp. That is to say, 8 or 10 lamps could be used in a gate road with a reasonable factor of safety. That is a very remarkable conclusion and opens up a very wide prospect for improved lighting below ground. On the other hand, I hardly follow the author's suggestion that portable lamps and "cabtyre" flexible cable should be provided for lighting the coal face. I think it is not unlikely that the miner, in the effort which we all know he constantly makes to improve the nation's output of coal, would become entangled in festoons of "cabtyre" cable. In my view, improvement will in practice lie in the direction of the better lighting of main and gate roads rather than in the better lighting of the coal face. There is one other aspect of the lighting problem. On page 29 of the last Report of the Secretary for Mines there is a Section dealing with diseases of occupation. Under that head is nystagmus, which is by far the most prevalent occupational disease amongst coal miners. Compensation for total or partial disablement is paid to 0·99 per cent of the workers, and it must cost the nation more than £1 000 000 per annum. The Report proceeds as follows: "The general consensus of medical opinion is that the essential cause is deficient illumination and that the only remedy is better lighting. . . . The problem of illuminating coal mines more effectively is perhaps the most important as it is certainly one of the most difficult of the health and safety problems confronting the coal mining industry." It appears to me that the author provides a remedy at hand. I should like to subscribe fully to all that Mr. Sparks has said, but on one point of fact he is not quite correct. He is not right in thinking that previous to the Senghenydd explosion no risk was thought to attach to electric bells. About six months before that explosion the coal owners of South Wales were circularized by the then Divisional Inspector of Mines for South Wales (Sir William Atkinson) and informed that such bells were dangerous, this as the result of an experience at Bedwas Colliery in Monmouthshire. The author begins the paper by saying that in view of the necessity for precise knowledge it seemed worth while to enter into the laborious task of determining the conditions for safety in working. In my opinion it is proved to have been abundantly worth while.

Mr. J. A. B. Horsley: It is very appropriate that the Institution should take an interest at headquarters in an industry in which electrical motors aggregating more than $1\frac{1}{4}$ million horse-power are used. The author remarks that the daily toll of life, and, may I add, the super-tax on maintenance, need never be paid if it were not for the element of human frailty. I suggest that is the important factor, for though research may prescribe limiting conditions to ensure safety

it must always be borne in mind that the best plans will often miscarry. An experiment is described in the paper which seems to show that there is no danger of open sparking where a cable suffers injury resulting in short-circuiting following a fall of roof, but there are on record instances where timber which had fallen with the roof has been set on fire in consequence of a short-circuit following such injury to an armoured cable. The arc is not always so transient or so controlled as to ensure that the dielectric will not take fire. With another type of cable it is not an uncommon occurrence, as a result of a short-circuit—not necessarily brought about by a falling roof or similar injury—for what are called "bursts" to occur, when the arc between the conductors persists long enough to burn a hole right through the coverings of the cable. I do not want to exaggerate or over-accentuate the possibilities of such accidents, because I feel sure that the risk of danger following a short-circuit can be diminished by a more extensive use of automatic protective principles other than those which are represented by fuses or their mechanical equivalent. I am very interested in the author's design of an earthing plate, but the attachment of the cable to the central rod should be at a point above the surface of the material with which the excavation has been filled in. The proportion which the number of accidents due directly to electricity bears to the total number of accidents which occur in mines in this country is very small, but it is the ambition of all engineers who are concerned with the use of electricity below ground still further to reduce the number of those accidents. To illustrate the influence of the human factor in mining problems I recount an incident which I heard of from the manufacturer concerned. As a coal-cutting machine motor repeatedly broke down, the maker visited the pit with the colliery manager. Upon opening the gate-end fuse box they found, in place of the proper fuse, a piece of substantial 7-strand cable. Explanations were demanded and given by the machineman with candour and vigour, to the effect that he had only been restrained by physical conditions from inserting a piece of the tram rail, such was his objection to automatic interference with his work of cutting coal.

Mr. S. W. Melsom: The author suggests that coal is an insulator, and I agree with him. He goes on, however, to talk of earth as a conductor, whereas dry coal and dry earth are both insulators. It is perhaps as well to realize that efficient earthing depends not only on the moisture in the soil, but also on the extent of the impurities in that moisture. It is only the impurities in ordinary water which in any sense make it a conductor. The question of earthing is becoming of the greatest importance not only in coal mines, and I should be glad if the author would say what he considers to be an efficient earth. In America an earth having a resistance of 100 ohms is quite common, whereas in this country the figure is often 1 to 2 ohms. The author mentions that it is necessary to pour water on his earth plate at intervals, but that is surely relying too much on the human element. The question is not merely an academic one. The Mining Regulations specify the insulation of the system in terms of the leakage current which may flow, the leakage current being expressed as a proportion of the maximum current. If the miner forgets to water the earth plate on any one day and there happens to be a leak on the circuit, the very fact that the earth is of very high resistance would of itself limit the current to a value lower than that required by the Regulations, whereas if the man had performed his duty a leakage current would flow and so indicate a fault. One would expect that in coal mines, where earthing is essential to secure safety to the operator, and where it is easy to make a really good earth connection, there would be a great deal of data on the matter, and it would be helpful if the author could give us a little more detail as to the actual resistance obtained and the methods used for determining the resistance of the connection to earth.

Mr. P. J. Higgs: The author states that it is not too much to say that upon the provision of an efficient earth the whole safety of electricity in mining depends, and I should like to add a few remarks on this part of the paper. In Section (10) he brings to the fore in a rather striking manner the subject of electrical endosmose. This is a subject which, although generally well known, is very apt not to be considered in its proper degree of importance. In a resistivity test on moist soil in a glass container, I found that electrical endosmose was very apparent; on the application of a direct current, in time the soil around the positive electrode gradually and visibly became drier, while that around the negative electrode became wetter. This was a simple though interesting example of the actual transfer of moisture through soil in the direction of the current. The earth plate illustrated in Fig. 10 would appear to be of good design, since it takes care of two important factors in the question of low-resistance value. The wedge-like sides tend to maintain, by the action of gravity, good contact between metal and soil, and provision is made for supplying water to keep the soil moist. The filling material of the earth cone, however, is given as stone and gravel, and I would suggest that coke or coke breeze (free from sulphur) is to be preferred in order to gain the advantage of conductivity along the third and horizontal edge. It may so happen that the earth connection is under a drying influence, in which case it is probable that the horizontal edge would retain its moisture longest, due to the rising evaporation of whatever moisture may still remain inside the cone. In such a case as this the horizontal edge may, if coke be used, serve to give the greatest conductivity to the soil, whereas with stone or gravel—being practically insulators—this advantage would be largely lost. I should be glad if the author would indicate in his reply the order of resistance to be expected from the earth connection shown in Fig. 10, since the results of American experience appear to point to the fact that it is an exception rather than the rule to obtain values of the order of 1 or 2 ohms with an earth electrode of limited extent. Practically the whole of the resistance of an earth connection is that due to the medium within about 5 or 6 ft. of the electrode. The medium underground would be coal, while at the surface it is soil. The resistivity of coal, even in its natural state, is of the order of that of an insulator.

Dry soil is also practically an insulator, but with a moisture content up to about 20 per cent by weight, as is common in its natural state, the resistivity is of the order of that of a poor conductor. Since soil and pure water are of themselves materials of high resistivity, it is evident that soil conductivity is primarily due to the dissolved salts in the moisture. This is substantiated by the effect of only small additions of salt to the soil around an electrode in very appreciably reducing its resistance. It would appear from American practice that about 30 ohms is an average value of the resistance of an earth connection of limited extent, and it is stated to be a rather difficult and expensive matter to obtain resistance values of the order of 5 ohms and less with such electrodes or system of electrodes. The use of the water-pipe system, a common earth wire, or an underground ring main of all available metal within a certain area, bonded together, is therefore advised. If such earth connections of unlimited extent are used, resistance values of the order of a fraction of an ohm can be obtained. The nature of an earth connection is such that with every appearance and impression of satisfaction the condition due to a high resistance may be quite unsatisfactory, and it would therefore appear that further information in regard to the important question of earthing as adapted to the needs of this country is very necessary.

(*Communicated*): The conclusions arrived at in the paper favour the use of alternating current at a fairly high frequency (of the order of 160 periods) and a relatively low voltage (of the order of 25 volts), for maximum safety in coal mines. A frequency of the order of 160 periods would be satisfactory for lighting, but would not be favoured for power purposes, since it brings in the well-known disadvantages of increased losses, lower power factors, and difficulties in design and speed regulation of rotating machinery. Since it is stated that it is in electrical haulage that development is likely to be greatest, this aspect is important. It would therefore appear that two a.c. supplies would be necessary, one of high frequency for lighting and one of low frequency for power. The use of a low-voltage supply would entail large currents for the same energy. The importance of this is shown in the relations between least ignition current and voltage; for 150 periods and 200 volts the least current is given as 23·5 amperes, and at 15 volts the least current is 175 amperes. For the same condition of safety against the breakage of a cable while delivering the same amount of energy, the least ignition current at 15 volts should be 330 amperes. It would therefore appear that the higher value of current for the lower-voltage supply is not of itself a factor of safety. The factor of safety is evident, however, in the case of a fault to earth, where the lower voltage would produce a smaller flash-over current. Generally, however, it is to be expected that an accidental earth in a coal mine would itself be of a high order of resistance such as strictly to limit the earth current; therefore the danger would be limited to that of short-circuit between conductors or an interruption of current due to a sudden break in the circuit. The author deals fully with the effect of current, voltage and frequency, but it appears to me that not sufficient reference is made to the factors of inductance, capacity, time, etc., as bearing directly upon the great importance of transients. American practice tends to recognize that the protection and design of electrical circuits against transients is of greater importance than the design for normal operation and working, since most breakdowns are primarily due to transient conditions. The transient conditions of the circuit would appear to be directly applicable to such a subject as sparking. An electric circuit generally contains two components of stored energy: viz. (i) that due to the capacity C ($\frac{1}{2}e^2C$), and (ii) that due to the inductance L ($\frac{1}{2}Li^2$). The capacity factor of energy is greater for high voltages, while the inductance factor is greater for high currents. In general, low inductance and high capacity factors are to be desired in order to decrease the intensity of sparking when breaking full-load current in a circuit. A change of current in a circuit requires a redistribution of the stored energy and an induced E.M.F., dependent upon the rate of change of current and the inductance of the circuit. In the case of a break of the circuit the current flowing will tend to fall to zero in a short interval of time; the stored energy of the circuit will appear practically entirely in the intensity of the spark at break. The induced voltage across the break would also momentarily reach a value which would primarily depend upon the constants of the circuit and the current, and be practically independent of the normal voltage of the circuit. It may happen, therefore, that the apparatus of an a.c. system may introduce greater inductances than would occur in a d.c. system, so that the transient phenomena in the former may be so great as largely to offset the experimental advantage shown by a.c. systems. The lower distribution voltages would also increase the inductance effect due to larger currents, and this again may partly offset the experimental advantage of immunity to dangerous sparking shown by the use of low voltage. Let us take a particular case of a short-circuit between two conductors protected by an overload circuit breaker. After the instant of short-circuit the circuit breaker will take time to operate; a typical figure is 0·18 sec., which for a 25-period circuit gives about $4\frac{1}{2}$ complete periods for the duration of short-circuit. During this time the current greatly increases and a large amount of energy is poured into the circuit. Now at the instant of break by switch, the intensity of spark will be a measure of the energy in the circuit in the transient state, and this may bear no relationship to the normal current and voltage of the circuit. It would appear, therefore, that possible transients, surges, oscillations, etc., of both voltage and current are very important in connection with the study of the use of electricity in mines.

Mr. W. M. Selvey: The author has had very special experience in investigating unfortunate occurrences. There is a tendency to attribute the cause of these, perhaps too readily, to open sparking, and hence to infer that electricity is a dangerous servant for mining work. I would contend on the contrary that it is, compared with other means, an exceedingly safe servant if properly used. Since a case has in some instances been allowed against electric ignition caused by open sparking, it becomes a duty to investigate thoroughly

all contributory conditions which go to make up a dangerous condition. Prolonged investigation has been made, and the net result is that these conditions can now definitely be arranged on a laboratory scale. A study of these conditions when compared with practice shows, what has always been dimly apprehended, how rarely a perfect parallel can occur. This study also indicates that the regulations as to the cessation of all working when the gas percentage rises to a certain value are both valuable and necessary, and if strictly followed would render almost impossible the combination of circumstances denoting danger. It is because of this perhaps, as Mr. Sparks has pointed out, that open sparking from bells as a danger was unsuspected for 30 or 40 years. That is to say, it took all this time even to suspect that danger was possible, and once attention was directed to the matter the risk was speedily removed without difficulty. Modern developments will, in my opinion, improve the factor of safety. They may be directed to using as high a pressure as possible for power, and as low as possible for lighting. High-pressure apparatus is more mechanical, requires but little current and readily lends itself to protective devices. More and more light should be used at low pressures, e.g. 50 volts and lower, and combined with high-pressure switchgear there is room for development. In an installation in which I am interested, I know of only three interruptions in four years on an extensive high-pressure power and low-pressure lighting system. Two of these were caused by flashing-over inside a closed oil-immersed controller. In each case the pit was cleared. Although some engineers may not think it good practice thus to interrupt work, my experience leads me to place the value of the moral effect higher than the cost of the interruption. I think that too much attention cannot be paid to the earthing system. In the system detailed in the paper, danger occurs due to the fact that the attachment to the earth plate is out of sight. Such an attachment would corrode away. It is better to have a prominent earth plate bricked around on the surface, with at least two visible attachments of the copper to the iron. It is better to have solid copper strip of substantial section bolted to the iron than to depend on any other form of attachment. For a certain distance from the earth plate it is well to reinforce the conductivity of the cable armouring by a special earth conductor, say as far as any considerable group of apparatus on the surface, in order to prevent any rise of voltage at the pit bottom and inbye. The author is here making a bold suggestion. Having definitely decided the dangerous conditions, by avoiding them it is now possible to use electricity freely at a place where (sooner or later) gas will occur, i.e. at the face. The paper contains the germ of a system of apparatus which would allow unlimited lighting at the face (at a frequency of, say, 150), and which could be destroyed by a fall without the slightest risk of ignition. Such a system would of course have to undergo extremely rigorous tests before it could be adopted and before the regulations could be modified to allow of it. I should be glad if the author would give in his reply some further indication of the type of apparatus that he has in mind for providing and controlling the supply of current.

Mr. F. O. Hunt (*communicated*): The paper is of great interest, not only for the immediate light thrown upon an involved subject but by reason of its promise of greater things to come. Coal and its economical winning are among the primary considerations in maintaining the commercial position of this country, for it was the application of the energy of coal to manufacturing which originally made this country the workshop of the world. That impetus has expended itself, and already the exhaustion of the more easily worked seams tends to make the cost of our coal increase. Consequently it is of the utmost importance that we should find better means of utilizing our coal. I suggest that this paper really represents part of the spade work which, by bringing to light the mechanism by which gases combine, may enable us to obtain electrical energy direct from coal gas or producer gas. It would seem that an understanding of the electrical conditions which promote combination might well be the stepping stone to the production of electrical effects by means of such combination. The effects of frequency seem to be very extraordinary, especially as the "presence of hydrogen raises the depression [in the curve of ignition]." The paragraph which follows (on page 488) is the most striking evidence I have yet seen with regard to the ionization theory of the initial stage of combination. I should be glad if the author would say whether the condenser to which he refers on page 484 is one having an air dielectric.

[The author's reply to this discussion will be found on page 509.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 14 JANUARY, 1924.

Mr. T. B. Morgan: I should like to ask the author if, in the course of his experiments on the general question of underground signalling, he has ever included the problem of telephones. The maximum voltage allowed by the Home Office rules for signalling apparatus is 25, whereas a magneto telephone (of which there are hundreds installed below ground) can easily generate from 100 to 200 volts. It would be interesting, therefore, to learn if experiments showed them to be dangerous or otherwise. I should like to know whether the author would favour one earthing point on the surface for the whole of a colliery undertaking, or whether he would prefer a number of earth plates at different points underground, such as sump holes, etc. Also, would he expect the same results in the earthing system of a colliery having, first, a three-phase system with the neutral point unearthed, and secondly, a three-phase system with the neutral point earthed?

Mr. B. L. Myer: The author states that the ordinary thin spark due to an electrostatic charge is not dangerous and is incapable of causing ignition of coal dust or gas; according to Section (3) of the paper it has not

been found possible to cause ignition of firedamp by this means. It would be interesting to know whether any experiments have been made in the deposition of coal dust from the atmosphere by means of a silent electrostatic discharge. In view of the statement that such discharges are not capable of producing ignition, such a method might possibly be devised to limit the amount of coal dust in the atmosphere.

Mr. H. Midgley: The use of pulverized coal in this country has up to the present been in the nature of an experiment, and amongst the troubles experienced have been explosions of the mixture of air and powdered coal during its passage from the pulverizing plant to the burners. As the powdered coal is practically coal dust it is, perhaps, not outside the scope of the paper to ask the author whether he would suggest that there is any possibility of these explosions having been due to static charges generated by the passage of the powdered coal through the pipes; or, alternatively, whether the heat generated by the friction of the powdered coal against the pipes may have been sufficient to fire the mixture.

Mr. W. Bolton Shaw: The curves of ignition seem rather to point to the conclusion that the only way to make electricity absolutely safe underground is to have a zero voltage and an infinite frequency. In the lantern slides showing curves for ignition by hot wires, I think that the author had in mind the question of the possibility of firing gas by the breaking of the globe of an electric lamp and the explosive mixture coming into contact with the glowing filament. The curves are, I think, given for only one gauge of wire, viz. 0·1 mm diameter, and it would be interesting to know how this diameter compares with that of the filament used in vacuum and gas-filled lamps, and whether, as one would naturally expect, the possibility of ignition increases or decreases with the size of wire. If the author has carried out a series of experiments to determine this relation, perhaps he will refer to them in his reply. I should also like to ask him whether he has made any experiments on the firing of gas or a mixture of gas and coal dust by mechanical sparks such as those produced when rotating metal rubs on metal. It is more or less held by mining electrical engineers that in the event of metallic sparks being given off by the rubbing of the rotor core on the stator of a motor of which the bearings are badly worn, there is a risk of these sparks firing any gas that may be present. This is a point of considerable importance, in view of the fact that open protected-type motors are not definitely prohibited in places where Regulation 132 of the Coal Mines Act applies. The ignition of gas by sparks produced by the rubbing of metal on hard stone is established by the fact that gas-lighters for domestic purposes are constructed on this principle. The earthing plate shown in Fig. 10 would appear to be very effective, in that the surface in contact with earth approximates to a hemispherical form (which is the ideal); the shape and construction are such that the earthing surface of the plate is kept in contact with the earth in such a way that any shrinkage or shifting of the soil will be followed up and the contact maintained; the connection to the plate can be substantial; and it is possible to get moisture to the contact surface in a simple manner. In criticism I would say that for colliery work something more substantial than $\frac{1}{16}$-in. galvanized iron would be necessary for the cone; the pipe should be not less than 2 in. steam piping; and the cable connection to the pipe should be above ground and not under the surface, as shown. Also, this connection would be better if made by screwing a heavy collar nut on to the top of the pipe with a locknut to fix it, the collar having screwed into it a stud of, say, 1 in. round copper, formed at its outer end into a terminal lug to which would be bolted the sweating socket on the end of the cable, or preferably the cable itself, looped and bound to form an eye.

Mr. H. E. Dance: In designing the case of an explosion-proof motor a pressure of 110 lb. per sq. in. is usually taken into account and a large margin of safety allowed. The space inside the average motor, in which gas can accumulate, consists of two distinct volumes of annular shape, one round the commutator and the other round the opposite end of the armature. These spaces are connected by the channels left between the coils of the magnet system. Now, if an explosion were to occur at the commutator end—and it is at this end that one would expect it to commence—the gases at the opposite end would, provided the channels were sufficiently small, be compressed before they exploded, and the resulting pressure would be considerably in excess of 110 lb. per sq. in. This phenomenon is well known, but I have never been able to obtain a figure which would represent within reasonable limits the pressure to be expected in a motor under these conditions. The figure of 110 lb. per sq. in. appears to be fairly reliable in enclosures where the explosion takes place freely. Can the author suggest an approximate maximum figure to be used when the explosion occurs successively in two volumes which are approximately equal and connected by a number of small channels, as in the typical motor?

Mr. H. Pryce-Jones: I believe that the filament temperature of a gas-filled lamp is considerably higher than that of an ordinary vacuum lamp. This being the case, I should like to ask the author whether the danger of explosion due to instantaneous ignition of gas, consequent upon breakage of a lamp in a "fiery" working, is any greater when the more modern type of lamp is employed. Also, if this theory is correct, has its verification been obtained as a result of experimental work or merely as the outcome of the comparison of the number of explosions over a given period in mines adopting the different forms of lamp?

Mr. A. E. Malpas: I have several times been down the pits, but have never really examined the construction of the lamps used. These were always handed out in the usual way after examination in the lamp room at the surface before descending the pit. Looking at the example of lamp now exhibited, one could hardly realize what would happen if the glass broke.

Mr. J. A. Morton: On page 486 an experiment is described in which an unarmoured cable is cut in two without an external flash being observed. In this case the trip gear was near at hand and operated quickly. In actual practice, however, the fault might be on an

inbye cable a considerable distance from the tripping gear, which might not operate so quickly as in the experiment. I should like to know which of two cables the author thinks is the better from the point of view of gas ignition, an inbye cable, bitumen-insulated and double-wire armoured, or an inbye cable, paper-insulated, lead-covered and single-wire armoured. In conclusion, I should like to ask whether the earth plate described has been patented.

[The author's reply to this discussion will be found on page 509.]

North-Eastern Centre, at Newcastle, 28 January, 1924.

Professor Granville Poole: The author's contributions to the subject of electricity in mining are well known and fully appreciated by the mining industry. It would be of considerable interest if he could give us a complete list of his papers, for the work described to-night is only a small part of the whole. The safety lamps which he has demonstrated mark a very considerable advance. An electric safety lamp which will indicate the presence of gas has long been in demand, and if the author can succeed in giving us one that will do this he will confer a great benefit on the mining industry.

Mr. C. Vernier: I am particularly interested in the section on electrical endosmose and the theoretical investigation in regard to the possible pressures produced. This explains clearly why so much trouble is experienced with the single-core leadless type of cable on d.c. networks when an incipient breakdown of the insulation occurs. It is well to point out that the same trouble is absent with lead-sheathed cables as the electrostatic field does not extend outside the cable, and even an incipient fault such as a small hole in the lead sheath is largely screened electrostatically by the adjacent lead sheath, and there is therefore no tendency for negative electrification to force water into the insulation. With positive electrification it is, of course, well known that the leadless type of cable dries out. The Hebburn case referred to in the paper was the outcome of a serious bitumen gas explosion resulting in loss of life, the explosion originating in a breakdown of leadless cables, and being caused by electrical endosmose. As the result of this accident it became urgently necessary to find some method of preventing similar accidents. Experience with a.c. cables indicated the great reliability of such cables, and a few experiments with leadless cables under the two different electrifications (see *Journal I.E.E.*, 1915, vol. 53, p. 360) very soon confirmed this to the satisfaction of all concerned. It was therefore decided to change over the network to alternating current, and the change, as stated by the author, has been altogether remarkable, resulting in a practical cessation of all cable faults and absolute freedom from liability to explosions. The improvement is immediate and certain, and the few faults which occur can clearly be traced to previous damage caused by the d.c. supply. Since that time a number of other networks have been changed over from direct current to alternating current, with equally remarkable results, and this is now becoming a common practice all over the country. The freedom from mains faults, and the great saving in maintenance charges are, it is needless to say, by no means the only advantages secured by such a change, other advantages being the saving of attendance charges by the use of static substations instead of rotary substations on large systems generating alternating current, and the ease with which increasing loads can be met by sectioning old networks and feeding them from additional static substations as required. It is certain that the practice of converting networks from direct current to alternating current will become general within a very short time. This question of endosmose should receive careful consideration in connection with cables for use in mines. Many mine managers favour the leadless type of cable, but it should be borne in mind that this type of cable from this point of view, and also from the point of view of fire risk, leaves very much to be desired.

Mr. H. J. Fisher: I should like to ask the author if he has succeeded in igniting gas by static sparks; it is quite possible to get these conditions when steam is blowing in the shaft or on the surface and has charged the lines or conductors. Extraordinary phenomena sometimes occur in mines. In one case two signal bells were burnt out under peculiar circumstances. They were worked on an incline with a single wire and earth return, and there was no electric power in that portion of the pit. This burn-out occurred at the time of a fault on an overhead 6 000-volt transmission line. The incline ran parallel to the line and was about 120 fathoms from the surface. I have often noticed stray direct current when testing armoured cables, at a time when all plant is shut down. I have been able to get low-pressure current up to 0·8 ampere; this I ascribed to the tramway system. Many years ago I carried out experiments with a view to getting flames to pass between machined joints, and at the same time to try to burst joint boxes with heavy short-circuits. I took a cast-iron box, 12 in. square, 8 in. deep, and $\frac{3}{8}$ in. thick, with $1\frac{1}{4}$ in. machined flanges, and short-circuited a fuse (designed to blow at 500 amperes) with plenty of power behind it. I never succeeded in passing any flame or in bursting the box, nor could I blow a cork, which had been fitted moderately tightly, out of the top. In regard to the experiment with the 3 000-volt cable, the potential danger lies not so much in a sudden penetration of insulation and the resultant short-circuit or earth, but in the fact that the fault may be switched in again and again, the sparking getting worse each time. An earth leakage protection would, I think, increase the safety. I have no doubt that the type of earth plate designed by the author will be very efficacious. I have always advocated the use of heavily galvanized iron plates, particular care being taken in regard to the connection of the earth lead to the plate, and also in regard to the insulation of the earth lead from the surrounding earth. I have always been an advocate of the earthed neutral. Unless the earthing system in the mine is kept perfect,

or earth leakage protection is adapted, one is apt to get sparking at haulage ropes.

Mr. J. Schuil: I should be glad to know if the author has any figures relative to the actual pressure obtained at the moment of explosion in the box which he exhibited. I believe that this was the original box made when I first started experimenting with explosion-proof gear and found difficulty in getting records of the pressure obtained. The origin of the gear was a report published about 30 years ago in the *Elektrotechnische Zeitschrift* describing experiments made in regard to the spreading of explosions through small tubes. It was stated that, providing the tubes are long enough in proportion to the diameter, no explosion can be communicated to the outside. This is now limited to very small tubes. It is also found that the shape of the box has a great influence on the violence of the explosion. The more cubic in form the box and the larger its capacity, the more violent the explosion. A very violent effect is obtained by blowing a very large fuse in a box. All the tests which I carried out were performed with direct current. The strength of the box may be very easily calculated from the formula given in Professor Unwin's book.

Mr. E. E. Grover: In Section (2) the author mentions arcs, and in Section (4) he refers to sparks. Does he consider that an electrical spark can ignite the dust or cause a coal-dust explosion if no gas is present? Table 2 clearly shows that a mixture of methane and dust will explode with a less percentage of methane than is necessary to cause an explosion when the methane is mixed with air alone. I take it that these explosions of dust and gas mixed were obtained by means of a sustained arc, and that a flame or sustained arc is necessary to start a coal-dust explosion. I notice that in these experiments the coal dust was added to gas and that the mixture exploded. I am under the impression that the addition of gas to coal dust does not affect it and that the coal dust cannot be ignited by means of an electric spark. I should be glad if the author would confirm this view.

[The author's reply to this discussion will be found on page 509.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 19 FEBRUARY, 1924.

Mr. W. T. Anderson: In dealing with inflammable gas it may be of interest if I exhibit the sketches issued by the old Home Office Department of Mines to illustrate the detection of gas in quantities of $1\frac{1}{2}$ to 3 per cent by observing the cap in the miners' safety lamp of the oil type, particularly as this has a bearing on the question of ignition by hot wires, or their equivalent hot gauzes, referred to in Clause 1. It was the personal opinion of Mr. John Gerrard, the late Divisional Inspector for the Lancashire area, that at least one great explosion was attributable to this elongation of the cap and consequent heating of the outer gauze to redness. With regard to the reference to the Eskmeals tests, surely these very elaborate experiments by the Mines Department were not made to convince possible doubters, as the author suggests, but to set up conditions for research as to how explosions could be minimized or actually avoided, for instance by stone dusting. In dealing with the small amount of risk attaching to breakdowns from mechanical causes on metal-sheathed cables when these are properly protected, it would have been of assistance if the author had dealt with the risk attaching to unarmoured trailing cables at the face, in connection with which leakage protective devices in the region of the gate end box are in a very undeveloped condition. In my opinion the greatest risk at the moment attaches, not to multicore trailers but to those of the concentric type which are still compulsory, in one form or another, when used with concentric mains—this apart from the obvious setback their continued use must cause to the advance of leakage (as opposed to overload) protection. It is not necessary to enumerate the anomalies which have dogged the development of these trailers. Suffice it to say that at the moment the outer of the type of concentric flexible cable generally used has to have a conductivity of 1·5 times the inner. To attain satisfactorily the requisite degree of flexibility this outer has to be applied in the form of braid or, more correctly, a series of braids. This entails a very short lay and consequent long length of spiral per unit of length of cable, involving such high electrical resistance that a very large number of compensating wires are necessary to attain the required conductivity. Hence a metal-to-metal comparison between outer and inner is actually in the nature of 3 to 1. This means that a concentric trailer becomes so stiff that the term "flexible" is a misnomer, and when one reflects that the life of a trailer primarily depends on its flexibility it will readily be seen that such stiffening as I have described leads to almost unavoidable mechanical breakdown, with undoubted subsequent flashing in that part of the mine where it can least be endured. Samples that I have examined undoubtedly bear this out, and it cannot be argued that such flashing was necessarily momentary. I feel very strongly that the use of a three-core trailer on a concentric system would be no more illogical than is the use of a four-core trailer on a three-phase system. It would undoubtedly be a great deal safer, and I should greatly value the author's views on this subject. In my opinion the ideal form of trailer is multicore with a lightly braided sheath round the insulated cores, to operate in connection with a leakage protection device. Such a sheath would not, of course, contain anything like the weight of metal required in cables of the purely concentric type. The suggestion of 25-volt lighting at the face opens up a most desirable state of affairs, though the transmission difficulties at that pressure are obvious. I have long expected legislation with regard to lower pressures for underground lighting, but at the moment the manufacturer has to face difficulties as they exist. He has to provide fittings which can be used, if necessary, on 500-volt power circuits for the series lighting of, say, haulage houses far inbye,

an extremely undesirable practice. He has to provide arrangements by which similar haulage or pump houses can be lighted, say, from concentric power cables by twin wires which he can only use by putting in a rotary converter between them. He has to provide light at the bottom and in the insets of upcast shafts when these are used for winding, where, in spite of the $1\frac{1}{4}$ per cent gas ruling, no human agency can possibly predict when a mixture of explosive proportions may happen to pass. I have recently been associated with experiments dealing with such contingencies. In this investigation we started on the assumption that although hollow fittings can, under certain conditions, be made flame-tight, no hollow fitting can be rendered gas-tight. Every colliery electrician knows that it is not practicable to fill small lighting fittings with hot compound, and this difficulty was overcome by using in its stead a plastic resilient plug. Incidentally, I should like to hear the author's views on what he considers to be the minimum safe flange for small fittings of the hollow type. Switches were similarly treated except for the infinitesimal spaces required for the make-and-break movement of the switch, which cavities were catered for by a long screwed surface through which the handle of the switch was operated. This only left a real cavity to be dealt with in the cubicles for the double-pole fuses, with which every reduction in cable size must legally be protected, and it was found possible so to construct these that, when blown under gross overload and filled with a mixture of firedamp in the proportions of 8·5 per cent, no flame on explosion was communicated to the surrounding atmosphere although it was charged with methane in the proportion of 8·9 per cent. In connection with the same subject of lighting, an anomaly to which attention might be drawn is that underground low-tension cables (up to 250 volts) need not, under certain conditions, be armoured. This, more than anything else, has been responsible for an appalling amount of bad work, as it is impossible to comply with the regulation demanding that such unarmoured cables shall be "efficiently suspended from insulators" without their coming into frequent contact with pit props and the like. In other words, conditions which are ostensibly allowed could be at once prohibited under the "General Safety" Regulation No. 132. With regard to sparking from metallic sheathings, the value of the paper would have been increased if the author had referred to the dangers involved by the continued use of concentric systems with bare outers. In my opinion the carrying of any heavy current by means of bare conductors in unsuitable places, such as safety lamp pits, should be rigidly prohibited. As a result of such currents, I myself have seen heavy sparking between haulage ropes and jockey pulleys 2 000 yards inbye and have known of an authentic case of a boy relighting his lamp between the armour and the nearest tramrail. In this connection I do not refer to concentric systems with insulated outers, and I see no reason why the Government should not allow systems of this class to be mixed with twin systems, a practice which, according to the strict letter of the law, is at present inadmissible. I disagree strongly with connections to earth plates being made in the ground (as shown in Fig. 10). Many years ago I adopted an arrangement, which has subsequently become to a large extent standardized, of installing nests of cast-iron pipes in such a manner that all connections to the busbars crossing their surfaced flanges were always visible and readily accessible. This is highly desirable, not only on account of dissimilarity of metals but also on account of probable rapid action set up by the coke or breeze, usually containing sulphur, with which earthing gear is generally surrounded. In connection with the same matter I would urge the vital necessity of periodical resistance tests being taken between earth plates on all colliery installations, and the careful logging of results. This not only allows comparisons to be made between the dry and wet months of the year but also goes a long way to ensure protection of the metallic sheathings of the shaft cables which are the most liable to electrolytic attack, particularly on large installations where there is bound to be a considerable amount of surface leakage underground.

Mr. W. Bolton Shaw: The paper adds the weighty argument of greatly increased safety to those practical considerations usually put forward in favour of the use of alternating current in preference to direct current for underground colliery work. The curves shown in Figs. 7 and 9 give the results obtained by varying the voltage and frequency of the current taken to fire methane by transient arcs. Presumably Fig. 9 shows the lower portion of curves similar to those in Fig. 7 but on an extended scale, and if this is so I do not understand why the lower part of the curves in Fig. 7 are curved while those in Fig. 9 are straight. The curves in Fig. 9 give the results for a 9·5 per cent mixture of methane in air. The author's arguments for using 25 volts at a frequency of 150 for safety reasons are apparently based on these curves, but one wonders whether this condition of the air is a more inflammable one, as regards the current necessary to fire it, than a mixture of methane in the presence of coal dust, for which a series of results are given in Table 1. Are the curves in Fig. 9 affected by the presence of coal dust, and, if so, to what extent? With regard to the question of lighting at 25 volts, I do not quite see the force of the remark that 25 volts is permitted everywhere in a mine, because, so far as I am aware, all ordinary lighting voltages are permitted everywhere in a mine, and open sparking where Regulation 132 applies is not permitted even on 25 volts. From the point of view of the Mines Act as at present in force, 25 volts does not therefore stand on any better footing than any other lighting voltage. Perhaps the author's suggestion is, however, that at 150 periods 25 volts is so safe as regards the firing of gas that open sparking might be permitted. Leaving aside the question of producing the necessary frequency, I see no inherent difficulty in lighting at 25 volts, but there will obviously be an extra cost in cables in order to avoid too heavy a voltage-drop for satisfactory illumination. The cost of this system, compared with that of one at 55 volts, which is quite a practical proposition and one which I advocate, would be something like 25 per cent greater, while compared with one at 110 or 220 volts it would be perhaps 30 per cent higher. There is a further practical advantage from the point of view of reliability and

maintenance, viz. the greater sturdiness of cables and lamps at the lower voltage. The author's argument depends, however, largely upon the question of frequency, and here the difficulty is in the frequency-changer. If a satisfactory frequency-changer could be designed of the same nature as a static transformer or preferably a transformer performing the double function of changing both the voltage and the frequency, the electrical industry would be greatly benefited. Coming to the question of lighting the coal face, the practical mining engineer will at once see a difficulty. The number of small flexible cables crossing the face from the lamps to the common cable supplying them would be a nuisance and very liable to damage. A single coal-cutter trailing cable, which is a much more robust affair than these small flexible cables, is always more or less in the way on the coal face and is a sufficient source of anxiety. On the other hand, with the element of danger from shock or burning or of sparks firing gas entirely eliminated, as the author claims, I do not think that there would be any insuperable difficulty in getting the colliers working on the face to accommodate themselves to the use and care of these flexible cables if they found, as they no doubt would find, that the greatly improved lighting was of substantial advantage to them in the getting of coal. A collier, from the very nature of his work, is accustomed to adapting himself to awkward and difficult conditions, and he would no doubt soon become accustomed to using flexible cables just as other workmen have become accustomed to the use of portable lamps in other awkward situations particularly unfavourable to the use of flexible cables. Mr. Anderson has drawn attention to the question of sparking from the earthed outer of concentric cables. Another and similar case of arcing which sometimes occurs is not always appreciated; that is from the armouring of an ordinary three-phase cable when a heavy short-circuit to the frame of the machine or switch or to the armouring of the cable itself occurs at the far end of a long cable (say, 1 000 yards long) and the earth current travels back by the armouring to the neutral point of the alternator. The drop of voltage in the armouring of the cable may be of the order of 100 to 150 volts, and if the armouring happens to be in contact with metal such as the frame of a haulage pulley or the haulage rope itself or the armouring of another cable, severe open sparking may take place at the point of contact.

Mr. S. H. Lee: That part of the paper which deals with the difference between a.c. and d.c. supply gives support to the attitude taken up by engineers over a long period, but one must now add to the conclusions that the a.c. supply is the safer. I should be glad if the author would say whether the adoption of his suggestion in regard to electrical transmission would improve the factor of safety. It is evident that the illumination on the coal face is, in the author's opinion, not what it should be. Are we to conclude that improvement would mean greater working safety, better working conditions for men, and an increased output? If this assumption is correct the most important point is freedom from electrical ignition. Can we rely on the system advocated to give this? It would be of interest if the author were to give particulars of the following apparatus to be used on a face 200 yards long where at present electrical cutters are being employed, with gates every 20 yards: (1) Type of fittings; (2) switch and protective gear; (3) number and candle-power of lamps; and (4) type of cable. In one case when starting into operation a new colliery power station a report came from the boiler attendant that while raking out the ashes he received a shock. I confirmed this fact and shut the plant down, but still the charge was present. On investigation a pipe joint over the boilers was found blowing, so a plate pointed at one end was fixed with the point set $\frac{3}{4}$ in. from the manhole cover handle, the other part in direct contact with the escaping steam. A spark $\frac{3}{4}$ in. long was obtained and photographed. Sparks are also caused by coal-cutter picks. I should like to have the author's opinion in regard to the use of bare wires for signal purposes, contact being effected by putting them together. Does he think that an insulated system would be safer if used on the Fryar Davis system? In this system switches are fixed every 200 yards on the road, and attached to the operating handle is a pull wire. This enables the bells to be rung from any convenient point. In Section (7), particulars of a penetration test on cables are given to ascertain if there was an outside flash. Taking in consideration the fact that all cables in a mine are armoured, why was only a lead-sheathed cable used? Again, why was a pointed wedge used? This in itself would prevent an outside flash. Has the author ever dropped a weight of 6 cwt. for 10 ft., the face of the weight being about 6 in. square (similar to the bottom of a girder)? I have used such a test on all types of cable after sprinkling the outside with petrol, with very interesting results. The earth plate illustrated in Fig. 10 is very practical, but I should like to know why the material used is only $\frac{1}{16}$ in. thick.

Mr. J. H. Buchanan: I take it that the curves in Fig. 9 are intended to show a comparison between the effects produced at different voltages, and there is undoubtedly some advantage in the lower voltage from the point of view of current required to cause ignition. But for a given amount of lighting it is necessary to consider the power which is used rather than the current, and, if the curves are examined from this point of view, I think it will be found that 100 volts appears to be a better pressure to use than 10 volts. Take, for example, the values of current for 10 volts and 100 volts at 140 periods—a convenient point on the scale. At 10 volts the current is roughly 200 amperes, and at 100 volts it is about 40 amperes. Now, 40 amperes at 100 volts is equivalent to 4 kW, while 200 amperes at 10 volts is equivalent to only 2 kW. The disadvantage due to the smaller current permissible at the higher voltage is more than balanced by the increase in available power. That is to say, if a spark occurs due to a break in the circuit, the higher voltage will be the safer for a given amount of power in the circuit. According to Fig. 9, at 140 periods it is safe to break up to 4 kW at 100 volts, but the danger point is reached at 2 kW with a 10-volt circuit. This would not necessarily apply to the case of a short-circuit, although the higher impedance of cables and transformers on the

higher voltage would tend towards making a short-circuit no more dangerous than on the lower voltage, for which the impedances would be extremely small.

Mr. G. S. Corlett (*communicated*): The most interesting part of the paper is perhaps the section dealing with the relation of frequency to the minimum current that will ignite gas. I gather that this is limited to lighting, as the cost of raising the frequency of existing power circuits would be prohibitive. On page 481 the author says: "Most of the accidents in mines are mechanical in origin, and are due to the poor illumination of haulages, or to the difficulty of keeping earth movements under continual observation." By "haulages" I presume he means "haulage roads" and not "haulage houses" and I take it that his second sentence hints, among other things, that it is now difficult to see when a fall of roof is likely to occur. It is common knowledge that many accidents, all too frequently fatal, occur due to falls of roof, and that such accidents would not have arisen if additional supports, provided close by for the purpose, had been fixed. The fixing of these supports is in many cases outside the discretion of the workman; that is to say, it is his duty to fix them at definite spacings. It is also unfortunately true that many other accidents arise due to the neglect to use one form or other of the many safety devices available, probably mainly due to familiarity with the particular danger, in short the same general motive or frame of mind which induces otherwise sensible people to jump off a train before it stops or to run violently after a tramcar. I fail to see how the most perfect illumination, or the most perfect observation of earth movements, would reduce these accidents at all. I do not want to imply that this neglect is only on the part of the workman; the owners at times do not provide the best appliances or maintain them in the best condition. It is also a regrettable fact that far too many of the accidents which do occur are officially classified as "preventable" and would not have occurred had something necessary been done. All possible steps should be taken to reduce these accidents. I should like to ask what is meant by the statement that "accidents are mechanical in origin." In the next sentence the author sets out the principal conditions on which safety in mines depends. It is not clear whether the author suggests that these points, which I agree embrace a wide range, deal with the whole question of safety, or merely with that portion due to electricity. Further, the tone of the paper as a whole is that (subject to the few items mentioned in the concluding paragraph, which will require watching) all the necessary information is available to carry out the work on these safe lines, and, for example, if one wants flame-proof apparatus he takes it out of stores or buys it as a standard in the open market. If that were true and the conditions set out by the author the only ones to be observed, the mining electrical engineer would have no cause to worry. It seems to me that the author is looking at the subject from the wrong perspective. The danger from this open sparking is primarily the ignition of methane with or without coal dust. There are, of course, other inflammable materials, but in an installation on modern lines and with fireproof motor houses, conforming to the regulations, the danger is small. The electric firing of methane is a rare occurrence and there are few cases on record that are conclusive. During the "electrical age," as the author describes the present era, there has been much bad electrical work, and some still remains, although it is a diminishing quantity. Nevertheless, this type of accident is fortunately infrequent. Though it may seldom happen, the precautions against it should not be relaxed in the slightest. In my view where the danger exists the precautions cannot be too drastic, because such an ignition may develop into one of those too-frequent disasters with heavy loss of life. Fortunately, the vast majority of plant underground is located where this danger does not exist and, except on some coal faces, the positions in a mine where electrical plant is required and where gas is likely to occur in dangerous quantities are few and far between. I am not clear whether by the expression "elimination of all sources of flame or open sparking" the author means that totally enclosed apparatus is to be used throughout. The standard ventilated squirrel-cage motor is certainly a potential source of flame, since no insulation is everlasting, and a liquid controller is the most suitable apparatus yet designed for heavy haulage, but it sparks openly. To my mind it is folly to prohibit these, except in the danger zone. As to the danger zone, i.e. where methane is likely to be present, I should like to emphasize that what is really necessary is a combination of apparatus which is jointly, as well as individually, safe. It is useless to have one or more links of such a chain defective. The author says on page 489 that real security for power circuits can only be obtained by complete enclosure, but I should like to know where such enclosed apparatus is obtainable of a safe nature. The simplest possible combination is a motor, switchgear and connecting cables. The author's experiment in a power house with a cable does not seem to me to be very convincing, and I do not think we have evidence to warrant our saying that with a fall of roof open sparking might not occur on a cable. As to motors, the Home Office Regulations apparently contemplate the use of open motors and appear to be based on the assumption that failure of the insulation and open sparking arising therefrom is not likely to occur simultaneously with an influx of gas. It is true that gas frequently comes slowly into a place and so can be detected in the early stages, but it is also true that it frequently comes without warning. For many reasons totally-enclosed motors are undesirable; and there has lately been a great output of certificates in regard to switchgear which is supposed to be safe in mines. I myself attach very little value to these certificates, as all the experiments are based on the ignition of the gas inside the enclosure by means of an induction coil. It should be remembered that in practice there will be no induction coil and the gas inside the enclosure will in all probability be ignited by some defect, probably a short-circuit. So far as I know there has been no research whatever as to the type of enclosure which will withstand the combined effect of a short-circuit and gas ignition when the supply is taken from a large power station. It seems to me

that there is a very real danger of the apparatus being completely smashed or at least of a hole being burnt through the covering, thus producing open flame. Again, these particularly dangerous positions are usually those remote from the shaft and consequently less likely to be visited frequently by the higher officials, and there is unquestionably to-day a very real danger of ineffective maintenance which I am afraid will continue for some time to come. It is most interesting to know that so much more current is required to fire gas at 150 periods than at 50, and this knowledge may at times be of great value. This is no doubt, however, limited to gas ignition, and current at 150 periods will fire cable coverings, wood and other inflammable material as readily as at any other frequency. I do not clearly follow what the author recommends as general practice for lighting collieries underground, but probably he means, in addition to what is usually done now, viz. shaft sidings, engine houses, main junctions, and the like: (*a*) That all lighting should be at 150 periods, 25 volts or thereabouts; (*b*) that haulage roads should be lighted; (*c*) that coal faces should in many cases be lighted; and (*d*) that lighting of other main roads should at least be considered. To illustrate this, I quote below data from an actual colliery on which I am at the moment professionally engaged; it is an old pit getting its relatively small output from two shafts and from various seams: (1) average daily output, 600 tons; (2) length of haulage roads along which this coal passes, 13 910 yards; (3) number of working coal faces, 22; (4) average length of each working face, 125½ yards; (5) total length of coal face, 2 761 yards; (6) average distance from the centre of each coal face to nearest existing substation, 1 132 yards. To adopt in this particular case what I conceive to be the author's recommendations, is no small matter. A good light to work by is of course desirable and as a rule directly promotes safety, but it is impossible commercially or practically to light all the roads of a colliery; it is a peculiarly trying experience to move to and from bright and dark areas, and may be dangerous. I have frequently bumped my head when a man walking in front of me on an underground roadway allowed his lamp to shine in my eyes now and then—the effect is quite blinding even if the illumination is of only 1 candle-power. Coal faces vary in dimension, fairly typical figures being: Height, 2 ft.; length, 300 yards; and inclination, 1 : 6. The machine would cut at night, and coal be loaded up by day probably by a mechanical conveyer; there would be a large number of wooden props supporting the roof and these would, after the machine had passed along, be quite close to the face, which would advance laterally about 1 yard each 24 hours. Assuming also that such a face could be fed at about the middle from one transformer and that there were 12 to 14 lamps, it follows that the wires and lamps must be disconnected each night, threaded back to the centre (because the props cannot be moved) run out again, fixed and connected up. Remember also that many faces are wet, and others very liable to falls. I know of no system of wiring which would last one month under those conditions, even if the law were modified to allow it. The whole tendency of modern legislation and practice is to restrict, and in the case of new collieries to prohibit, the travelling of workmen generally on haulage roads. Again, in the particular colliery that I have quoted, there are 14 000 yards of such roads. To light the whole of those roads the following would be required: Numerous motor-generators to raise the frequency to 150 periods; a double system of wiring throughout; feeders at, say, not less than 200 volts; distributors at, say, 25 volts; numerous step-down transformers and switchgear, as the economical area to be fed at 25 volts is small; and maintenance difficulties such that I do not wish to contemplate.

[The author's reply to this discussion will be found on page 509.]

South Midland Centre, at Birmingham, 12 March, 1924.

Dr. C. C. Garrard: With reference to the phenomenon mentioned by the author, viz. that heated platinum easily ignites gas, I should like to know whether the words "activation" or "ionization" are not other names for the catalytic action which, as is well known, is exercised by platinum in many chemical processes. I should be glad if the author would state what value of earth resistance can be obtained under practical conditions from the earth plate illustrated in Fig. 10. He has shown several ingenious lamps for detecting gas, but are the electrical methods which have been proposed not reliable? As regards the general question of the use of electricity in mines, the author clearly shows that there are certain limits of current and voltage below which there is no danger of gas ignition. I take it that it is not proposed to install any system working below these limits without the usual safeguards which have now become good standard practice in collieries. The Regulations say that open sparking shall not be allowed in the specified zones. Open sparking is defined as a condition of affairs which will allow an internal flame or explosion to be communicated to an external explosive atmosphere. This is, I think, explicit and entails the use of flame-proof enclosures. Research is undoubtedly wanted on the flame-proof enclosure question. Wide differences exist in the practices of the different countries. It would appear from Bulletin No. 68 issued by the Bureau of Mines, Washington, on Electric Switches for Use in Gaseous Mines, that colliery owners in the United States are prepared to regard as explosion-proof, apparatus which does not pass muster here. On the other hand, I understand that in Germany the problem of making, for example, a complete motor flame-proof has been given up as insoluble, and the rules issued by the Verband Deutscher Elektrotechniker for the use of electricity in collieries have been modified, permitting the use of what we should call motors with open-type windings (provided they conform to certain requirements as regards insulation), simply making the slip-rings flame-proof. Dr. Wheeler has given us data from which it would appear that it is a very simple matter to make any enclosure flame-proof. All that is required is to

use a $1\frac{1}{2}$ in. flange with a $\frac{1}{32}$ in. gap. This, I understand, has been shown to prevent any dangerous pressure occurring due to an internal explosion, and at the same time to prevent the egress of a dangerous flame. Personally, I had not thought that the problem was so simple. I think, however, that the fact that these varying practices exist in different countries shows the need for continued research on this question of flame-proof electrical apparatus.

Mr. A. E. Angold: The curves which deal with the ignition temperatures of various mixtures of gases appear to cover all possible variations, but those showing the effects of transient arcs do not take into account possible variations of speed of break and the size, shape and material of the arcing contacts. I understand that the speed of break used was intended to represent ordinary switching speeds. If the author had used the slowest break that is likely to occur in practice, quite different results would have been obtained. I suggest that one of the worst conditions that will be encountered is the case where a cable is pulled out of a terminal but one strand is left in poor contact with the terminal, resulting in overheating and finally in arcing. My experience has been mostly with means for starting and maintaining arcs, but such experience has shown that there is greater difficulty in maintaining low-periodicity arcs and suggests that they would be safer than the high periodicities tried by the author, i.e. they would give just the opposite effect when the particular conditions suggested above occurred. It will most probably be found that no circuit is safe unless it is an a.c. circuit, is protected by a non-inductive resistance and has a voltage below the minimum arcing voltage of the metals used, viz. 25 volts or less. The author's theories as to the conditions of transient arcs which do or do not fire explosive gases seem to be too much influenced by the theories due to investigations into mercury-vapour rectifiers, thermionic valves and the like. In all these the positive pole does not get hot enough to give any character to the phenomenon as a whole, whereas arcs as known to the power engineer are for him so much metal melted and probably evaporated from the positive pole. With a.c. arcs both poles suffer because they are *positive* in turn. The temperatures of the positive pole and of the greater part of the gases are governed by the material of the positive pole. The hot spot (on that pole which is negative for the time being) from which the true arc starts, and the central core of gases which acts as the conductor, will also at times have their temperatures modified by the temperatures of the gases surrounding them and thus more or less delay the restarting of the arc at each half period until the voltage has risen sufficiently to suit the existing temperature. The chief interest that the power engineer has in this characteristic of the arc, namely that it can only start from or shift to a hot negative conductor, is the opposite fact that the other or positive end will transfer itself to a cold positive conductor. It would thus seem preferable to earth the negative pole on d.c. systems and thus prevent arcs in switch boxes, etc., from jumping across to the iron case as they have a habit of doing when the earthed case is positive.

Professor W. Cramp: I propose to deal with the difficulties which arise when one compares the author's results with those of other workers. In attempting such a comparison, the first difficulty which presents itself is that of understanding what is the meaning of the terms used to distinguish the various forms of discharge. The author, for instance, divides his into two categories, one called "disruptive" and the other "break sparks" or "transient arcs." On the other hand, Mr. J. D. Morgan, whose work on this subject is well known, speaks of two types, which he describes as "capacity" and "inductance" sparks respectively. It is important that this question of terminology should be settled, and I hope that it may be taken up by the B.E.S.A. We may distinguish at least four types: (1) The silent discharge or glow which exists between two electrodes when the circuit conditions are such that ionization of the intervening air can only take place in regions near the electrodes. (2) An intermittent discharge of an oscillatory character which takes place when the pressure across the electrodes is increased beyond that under (1). (3) A succession of discharges, each started by a discharge of the form under (2), but hot enough to cause combination between the nitrogen and oxygen of the air, and consequently to set up a flame, which is extinguished as it lengthens. (4) A low-pressure arc formed when the current through type (3) is increased, and which depends chiefly upon the vaporization of the electrodes. Oscillatory effects are present in type (2) and can almost always be traced in (3) and (4). But for a given sparking distance the voltage is higher for types (2) and (3) than for type (4), although by properly adjusting the circuit the discharges may be made to merge one into another. In any case the circuit conditions determine the type of discharge, and it is of the utmost importance, therefore, for such work as the author's, that the circuit conditions should be rigidly stated. The information at our disposal only records the fact that the circuit was "non-inductive"; that is to say, according to the author, on a frequency of 50 its power factor was 0·95. This, however, is insufficient. The time-constant that is unimportant on such a frequency may be of the greatest possible importance on frequencies such as are obtained with oscillating discharges, and there is no doubt that some of the sparks with which the author has been dealing were of this nature. The frequency might easily have been 100 000, and might possibly have been as much as 1 000 000, in which case not only does the above time-constant become of supreme importance but it will be modified by the presence of capacity in the windings and terminals. No information is given with regard to the latter, although it has been repeatedly shown that the size and form of the electrodes modify not only the type of the discharge but also the energy required to fire a mixture. Evidence of this is to be seen in Mr. Morgan's paper in the *Philosophical Magazine* (1923, vol. 45, p. 969). This again introduces the question of the energy required to fire a given mixture, which is stated by the author to be 0·03 joule, although Morgan and others have obtained explosions with as little as 1/10th of this figure. This discrepancy is probably due to the inaccurate method of calculating the energy, which is often based upon the maximum energy in the

capacity in circuit. But this maximum energy has no connection whatever with the energy absorbed by the spark. It is possible to have a circuit containing a spark gap, with suitable circuit conditions, in which a current of 50 amperes is maintained by the charge and discharge of a condenser, and yet the energy expended in the gap may be almost negligible. So long as such methods are adopted, Mr. Morgan's remark, that the results obtained by different investigators can never be comparable unless carried out with identical apparatus, will remain true. The question as to whether the firing of a gas is thermal or electronic has, in the author and Mr. Morgan, two supporters of the rival theories. This matter does not seem to me to be of importance, as the minimum energy required can probably be expressed in terms of either theory. The attempt that Mr. Morgan has made, in the paper quoted above, to show that this is a thermal question is to me not very convincing, since the assumptions made are too rough to be acceptable, and I concur with the present author that many of the phenomena are more easily looked at from the point of view of the discharge of electrons.

Mr. W. Wilson: By giving much definite information as to what is safe, as well as what is dangerous, the author has afforded data upon which important results can be based. I was particularly interested in his reference to the comparative effect of direct and alternating currents upon the insulation of cables. In the case quoted at Hebburn it is to be presumed that all the faults took place upon the negative cable, since the tendency would be to expel the water from the positive one but to drive it into the former. I am particularly interested in the testing of electrical apparatus for safety in a gaseous atmosphere, and I should like to ask the author what in his opinion is a fair method of exploding the test mixture in such an apparatus. Since the exploding agent in practice will in nearly every case be a transient arc, it seems to me that a spark from an induction coil cannot be a thoroughly representative means and may result in a weaker explosion than would be given under actual working conditions. As a preliminary to the routine testing of a range of contactor boxes for mining work, measuring about 3 ft. × 2 ft. × 1 ft., I carried out a number of experiments with various forms of transient arc for exploding the pentane mixture used for testing purposes. The three methods experimented with were, first, a 5-ampere fuse; secondly, a 50-ampere fuse; and thirdly, the actual 100-ampere contactor that was to be fitted in the case. The pressures produced, as recorded in the small pressure-indicator described on page 76 of my paper in this volume of the *Journal*, were 16, 30 and 40 lb./sq. in. for the three species of arc respectively, these being approximately in the ratio of 1 : 2 : 2·5. These were the average of a number of tests which were not carried out consecutively, and gave results which were quite close together for each variety of arc. It will be seen that there is a considerable variation in these, and if the first method had been employed to investigate the safety of the box, or if a spark had been used, it is quite possible that the apparatus would have been actually unsafe although it survived the test. It would appear that the explosive pressure produced has a definite bearing upon the safety of the apparatus, for not only must the disruptive strength of the enclosure be adjusted to resist the maximum pressure, but the transmission of flame through the relief apertures would also vary approximately with the pressure produced. My own opinion is that the igniting means should give at least as high a pressure as that which can occur with the standard apparatus. In connection with these tests it is of interest to record that the explosion pressure produced with the contactor when closing the circuit—the ignition being due to the small arc formed by the usual rebound of the moving contact through about $\frac{1}{32}$ in.—was at least as high as that developed by the breaking of the current, producing an arc originally $\frac{3}{4}$ in. in length, which was stretched out to extinction by the magnetic blow-out. Some observations in connection with the use of relief apertures are perhaps worth describing. One of the most convenient methods employs a large number of small holes drilled in metal between 1 in. and $2\frac{1}{2}$ in. thick. As the result of varying the number of holes and testing each variation, I have found that the explosion pressure is approximately in inverse proportion to the square root of the number of holes. In connection with ironclad oil switches, there is sometimes a diaphragm in the explosion chamber, separating the tank from the box containing the trip mechanism. With the volumes of these chambers approximately in the ratio of 1 : 3, and firing first in the smaller chamber, it was found that the explosion pressure was approximately twice that of a similar explosion in the box without a diaphragm. I have carried out a number of tests to ascertain whether the position of the holes has any effect on the relief, as one or two early tests seemed to indicate that the box behaved somewhat like a Chladni disc, having nodes and antinodes representing the positions of maximum and minimum pressure relief. Sets of 100 1-in. holes were located on various representative portions of the box, but no pressure-change with different positions of the holes was observed. This box contained a diaphragm as described above, the holes being located in the larger compartment.

Mr. F. Forrest: A great deal of attention is now being given to the use of pulverized fuel for boiler firing in electrical generating stations. Although progress in this direction has been much greater in the United States and on the Continent than in this country, there is no doubt that many stations in Great Britain will install pulverized-fuel plants during the next few years. One of the risks attendant upon the use of pulverized fuel is the possibility of an explosion occurring if a naked light or an electric arc is brought into intimate contact with a quantity of this fuel which may, due to leakage from the fuel containers, be blown out into the atmosphere. The author states that the cloud must always be dense before the mass of dust could transmit an explosion, and Fig. 1 indicates that with about $7\frac{1}{2}$ amperes at 250 volts a dense cloud would be ignited. How dense the cloud must be before there is a risk of explosion is very difficult to define, but if the author can give some information on this point it would be of great interest to those who are considering the use of pulverized fuel for power station work.

Mr. W. W. Wood: From an examination of Fig. 9 it would appear that for each voltage and frequency there is a certain safe current limit, and below this limit the interruption of the circuit by even a slow-break open switch will not fire an explosive mixture of methane. I am not clear, however, as to how far the method of supplying the current affects the result, and I wish to raise the following points: (1) Assuming that a safe current (say, for example, 130 amperes at 20 volts and 160 periods) is being supplied from a step-down transformer and that the current is interrupted by a slow-break switch in an explosive mixture of methane, can we be certain that this will not cause an explosion? (2) Assuming that a similar safe current is being supplied from a transformer and that there is such resistance or reactance in circuit that the current cannot exceed the safe limit determined from Fig. 9, even on a short-circuit of the supply, can we take it that an open short-circuit will not fire the gas? If such safety can be assured then there are many cases where small transformers could be installed in safe places underground and used to supply lights in places where electricity could not be used under ordinary conditions. Although the safe current is equivalent to only a small amount of power, and the available amount of power for the lights would be further reduced by the resistance or reactance necessary to limit the short-circuit current to the safe figure, nevertheless there are cases where the possibility of giving light in this way would be of considerable advantage.

Mr. R. Orsettich: The investigations described in the paper are exceedingly interesting to manufacturers of electrical apparatus, in so far as they give a clear insight into the conditions which bring about the explosion of gases when such apparatus is installed in coal mines. The position with regard to manufacturing such apparatus is as follows: On one hand the mining industry requires the supply of electrical machines which must, therefore, be produced by whatever knowledge of the conditions is available; while on the other hand the Mining Regulations issued by the Home Office, as embodied in the Coal Mines Act of 1911, put very severe restrictions on the use of apparatus in coal mines, and particularly in such workings where Regulation 132 applies. This Regulation states that apparatus must be such that no open sparking is possible. The Act, however, does not define clearly what open sparking means, does not fix a limit to the application of the Regulation to any output given by the apparatus, and at the same time requires a guarantee to be given by the makers that the apparatus is suitable for working under the above conditions. A restriction of this kind would be almost equivalent to the abolition of electric applications in workings where gas may be present, and the only Regulation which helps matters at all is that which states that as soon as gas is present to an extent of 1½ per cent the electrical supply must be cut off. Manufacturers have been busy for a considerable time with the framing of some additional rules to define the above points, which at the same time would be acceptable to the Home Office authorities. Although the framing of these rules is not complete, machines have to be supplied as required by the mining industry, and it is left, therefore, to independent manufacturers to satisfy themselves that the machines are suitable to the best of their knowledge. The first step was totally to enclose the machines, both d.c. and a.c., in order to endeavour to exclude gas. It was soon found, however, that this was an impossible task because, no matter how tightly the enclosures are made, gas will enter the machine through "breathing," caused by the expansion and contraction of the air contained in the machine. It was, therefore, necessary not only to make the machine totally enclosed, but also to make the enclosures sufficiently strong to withstand a pressure of about 130 lb./sq. in. which would be produced by an explosion, and also the shock due to this pressure being suddenly applied. The use of cast iron for the enclosure of such machines, especially for larger sizes, was soon found to be impracticable, and resort had to be made to cast steel in order to obtain the necessary strength without excessive weight. The use of cast steel for all parts of the enclosure, such as bearing brackets, covers, inspection doors, etc., would not only increase the cost of the machines but would also make their delivery impossible in most cases, seeing that such parts are not stocked and that the quantities required are subject to a varying demand. In getting out such designs some additional points must be taken into account, such as the possibility of an explosion blowing out the oil from the bearings, and thereby causing firing of bearings through want of lubrication, also the possibility of dust being ignited where small gaps would allow the gas to escape. About the year 1907 investigations with various types of relief openings were made in Germany, and as a result the German system of enclosure was developed. This consisted in providing a number of circular or square openings in the casing; the periphery of each opening was fitted with a number of multiple gaps, consisting of thin brass plates placed a small distance from one another, the cover of the opening being solid. Such enclosures work quite satisfactorily, and the gas ignited by an explosion can escape through the gaps and is cooled sufficiently in passing along the plates to become harmless to any gas surrounding the apparatus. The main defect of this system, apart from the fact that the plates can be easily damaged, is that coal dust settles between the plates and closes the gaps and that such coal dust can be ignited by an explosion. The policy adopted by my company in producing enclosures for motors for mining work has been, first, to make them in such a way that the pressure inside should not exceed 30 or 35 lb./sq. in.; and secondly, that the relief valves used should be made in such a way that whilst cooling the gas they should always be kept free from dust, thereby avoiding danger of outside ignition. The relief valves consist of thick steel plates through which a number of very small holes are drilled, the number of holes and the area of the plates being proportionate to the volume of gas contained in the machine. A spring lid is fixed on top of the relief valve and is made to open under the pressure of the gas from the inside. The apparatus made in this way is tested by exploding a mixture of methane or pentane inside the machine by means of a sparking plug, and a test is made by endeavouring either to ignite some guncotton or petrol

fumes outside the apparatus, or else to enclose the apparatus in a second chamber which is itself filled with an explosive mixture. Already a large number of machines have been tested in this way, and a certificate is issued with the machine stating that it has passed the explosion test satisfactorily.

Mr. G. M. Harvey (*communicated*): In considering the influence of frequency, the author says nothing as to the material of the electrodes, except that they are of metal, and gives no explanation of the use of iron and nickel in Fig. 8. A curve for zinc would have been of greater interest, since the armouring of a cable is invariably of galvanized-iron wires. It would be of interest to learn whether the author has found the so-called "non-arcing" properties of zinc to affect the production of ignition. The author states that he has succeeded in firing gas by the sparks from a grindstone. This is specially important, since I understand that other investigators have completely failed to obtain ignition by this means. With regard to the devices described on page 484 for absorbing the discharge of energy from the windings of a bell, most of these possess the disadvantage that they may accidentally become inoperative, leaving the circuit in a dangerous state. In a system which I have recently patented, self-induction is entirely eliminated from the signalling circuit by introducing a thermionic valve as a relay. The circuit that is closed to give the signal is the filament circuit of the valve, while the anode current operates a sensitive, flame-proof relay and rings the bell. The note on page 485 as to the difficulty of procuring ignition by hot tungsten filaments is most comforting, but I would ask whether the author has investigated the possibility of ignition by the breakage of gas-filled lamps—a somewhat different case. The explanation on page 488 of the droop in the curve shown in Fig. 7 is somewhat difficult to grasp, and, although the author states that the circuit broken was non-inductive, I would ask whether this was actually and literally the case, since the effect would appear to be rather one of resonance, the natural frequency of the circuit being in the neighbourhood of 360 periods. This would be possible for very small values of L, although a somewhat large capacity would be required in the circuit. The voltage-rise might then be sufficient to ensure that the energy discharged at break would correspond to the dotted portion of the curve. However satisfied one might feel as to the safety of lighting the coal face with high-frequency current, it is to be feared that the practical difficulties of the scheme would be insuperable. A trailing cable supplying a coal-cutter, and lying in coils about the face, is bad enough, but if each man is to have a trailing cable attached to his lamp great confusion would result. The question of increased illumination at the face is one of extreme difficulty, owing to the total lack of reflecting surfaces. The present electric safety lamps of 1 c.p. are often trying to the eyes, and if an 8-c.p. lamp is to be placed in the lantern the concentrated light would certainly cause a glare which would be injurious to sight. To diffuse such a light at all adequately in such a small space as the lantern of a safety lamp would be almost impossible. Illumination by means of ordinary mining-type well-glass fittings, wired with armoured cable, and provided with frosted well-glasses, the whole arranged so that it can readily be advanced with the face, would be a much more satisfactory method but is at present prohibited by the Mining Regulations. With regard to electrical oscillations in cable sheaths, experiments which I have recently made show the impedance of the armouring of a cable to be lower than that of a plain tube, instead of higher as stated by the author. That the danger is a real one is shown by a case which has come to my notice, in which sparks are alleged to have been seen running along the armouring of single-core cables on a d.c. supply controlled by oil-break switches, when heavy currents were broken. The greater part of the paper appears to be a distinct challenge to the supporters of the thermal theory of ignition, and their reply will be of great interest.

[The author's reply to this discussion will be found on page 509.]

North Midland Centre, at Leeds, 18 March, 1924.

Mr. M. Wadeson: There is no doubt that the use of electricity in mines is steadily increasing, and it is to researches such as those described in the paper that one must look for information as regards the prevention of the occurrence of dangerous circumstances. It is generally on such work that regulations are framed —not always wisely—and one of the striking points which the author brings out is that direct current is much more dangerous to use than alternating current. Unfortunately, in most of the installations in which direct current has been used, the equipment has been installed in the most dangerous way, because this was generally done before the Regulations which are now in force for such installations had been drafted. I have seen a number of d.c. installations, and in many instances they were equipped with an ordinary open-type switchboard below ground, with the ordinary pattern of open-type circuit breaker mounted on the board. After what the author has said, it can easily be realized that if gas had been present there would have speedily been an explosion. I have found that on a.c. installations it is generally best to rely upon a high-pressure supply with some form of leakage trips to give the greatest freedom from breakdown. When a fault does occur the whole supply is cut off before any open sparking occurs. I think it can be said that the loss of life in coal mines from accidents of every kind which can be attributed to faulty appliances—or rather, I should say, defective appliances or faulty practice—has been steadily decreasing, but accidents due more particularly to the human element have not shown any such decrease. Very often where suitable precautions are taken to safeguard the use of electricity, the human element speedily puts those precautions out of operation. Electricity underground is generally handled by men who are unskilled in its use, and one of the first essentials

is the training of such men to understand what to do and what not to do with the apparatus. The apparatus must, of course, be made as safe to work and as fool-proof as possible. Under the head of accidents largely due to the human element come those which are concerned with haulage, and the author points out that the more efficient lighting of the main roads at those points where men are employed is undoubtedly a great factor in reducing such accidents. In addition, it is more efficient in saving time and congestion. As to the suggestions that the author makes with regard to the lighting of the coal face, of course the present Regulations would need to be amended before that would be allowed. But if his researches were to bring about such a state of affairs, I think that the coal-mining industry would owe the author a very heavy debt. One of the great economic burdens which the industry now has to bear is that due to the disease of the eyes known as miner's nystagmus, and it has been almost unanimously agreed that the primary cause of that disease is inefficient illumination, more particularly at the coal face where the illumination is low and the absorptive power of the coal is high. In an abstract of a report on signalling with bare wires, it was stated that transformers should not be used for bare-wire signalling. In the technical Press there was a letter written by the Chief Engineer of the Powell Duffryn Steam Coal Co., in which he took exception to that statement and said that he had found that transformers were not only more reliable but were safer to use than batteries. Does the author think there is any other objection to the use of transformers than the fact that the low-pressure winding may be charged to high pressure? This can, of course, be avoided by the introduction of an earth shield between the windings.

Mr. R. Holiday: I feel that the apparatus mentioned in the paper may work perfectly well in the laboratory or in the hands of a skilled workman. In practice, however, a couple of thousand of the lamp gas-indicators, say, would have to be brought out between 2 o'clock and 2.30 and placed in the lamp room where half a dozen boys would dismantle them for cleaning. What would be the condition of the little batteries and bulbs in the course of a week or so? One must look at these things from the practical everyday point of view. The collier does not, as a rule, like a new thing. I was a pioneer in introducing a number of things for electrical work at collieries, and I found that if one has sufficient enthusiasm and also sympathy with the conditions under which the man works, and lets him find out (though it takes time) that one is really wishful to make things better for him, he will finally agree to use what he calls the "new-fangled" thing. It is possible that if the indicating device of the lamp were made of a stronger pattern, the men might be led to realize that it was to their benefit. I think that the tendency nowadays is to adopt the electric type of miner's lamp and gradually to displace the oil lamp, which possesses all sorts of disadvantages. My own opinion is that the alkaline cell will be used in the future for mine lighting. Before the war we decided, because our oil lamps did not comply with the new Regulations, to install an entirely new set of lamps, and I came to the opinion that the alkaline type of cell was the best. A short time ago one of these cells which was delivered 10 years ago was unpacked and found to be in perfect condition. I do not think that any acid cell would have retained the charge for such a period. With regard to the arrangement given in the paper for connecting on to a cable at the coal face, it has to be remembered that in this district, with the thick seams, there are not likely to be so many coal-cutters. The coal-cutter is peculiarly of advantage in the thin seam where the coal is cut small by the men in order to undercut it: 25 per cent of the seam may be broken into small coal in under-cutting where the floor or top is too hard to be cut by the pick. In districts where there are thin seams the coal-cutter is of great advantage, but there does not seem to be any call for it in the thick seams. I hope that research work such as that described in the paper will induce colliery proprietors to give new methods a trial to enable those who have done the foundation work to suggest improvements to make apparatus of real safety. I feel that there is at present too great a tendency to impose new rules on collieries. For example, at the collieries with which I am connected we recently converted the whole of the plant underground from direct current to three-phase alternating current at 3 000 volts. That is the third time that the installation at that colliery has been altered to comply with new regulations.

Mr. H. Moss: The author has raised a good many points of vital interest to the mining engineer and the mining electrical engineer, but there is one thing in particular that strikes me in connection with his remarks in regard to safety lamps. Is it suggested that the little signalling device with the red lamp inside should be used by all the miners, or only in isolated instances or in certain districts where the lamp is to be made permanent during the day's work? The author suggests in one case that a bell could be connected, and I hardly think he means that the miner should walk about all day with a lamp with a bell attached to it. I assume that that particular lamp would be hung up in what would be called a gaseous or semi-dangerous position where gas was likely to appear. I am particularly impressed by the fact that the higher the periodicity the safer it is from the point of view of ignition of inflammable gas that may be present in any particular district. I understand that a plug switch is used in connection with the lighting of the coal face, so that the lamp cannot be withdrawn until the switch inside is broken. If that method were adopted I take it that in each section of the coal face the suggestion is that one of these batteries should be installed in that position so that the miner could attach his lamp to it by a suitable length of flexible cable and get a much better illumination at the working face. That would add considerably to the expense of electrical equipment in the mine, and it would entail carrying batteries back to the surface each day to be charged, or, if the supply were alternating, special cables to charge the batteries at suitable depots in the mine. I should be glad if the author would say whether the apparatus which he describes is in use in any particular mine in this country, and whether he can give any

figures as regards increased production that has been obtained by increased illumination at the coal face. I gathered from his remarks that this country is very much behind Japan, for instance, and one wonders, if electricity has all these advantages in the mine, how it is that mine-owners in this country have not adopted it on a much larger scale than they have done. I agree with a previous speaker that it is important that at all junctions on the main haulage ways a very good light should be provided for the men and boys working there. This will minimize the risk of accidents caused by collisions with loaded trucks. In common with a previous speaker, I have had experience with open-type switches and starters, and every machine 25 years ago was of the old-fashioned type. It is evident that the apparatus would not have been safe if there had been any gas present in the mine. Coal-cutting in some mines was being done rather extensively 25 years ago by compressed-air machines, and in the case of a gaseous mine one wonders whether, instead of taking the mains right up to the coal face and running coal-cutters by electricity, it would not be safer to use air-compressors driven by three-phase motors in what would be a safe district, and then to use compressed air at the coal face itself.

Mr. J. D. Walford: Mr. Holiday, who is General Manager of the colliery company with which I am engaged, has covered many of the points to which I desired to refer. I should like to mention, however, that a great many collieries which have changed over to alternating current still use direct current for signalling on the main roadways. Is there any reason why we should not use alternating current for that purpose also?

Mr. G. W. Jenkins: I take it that the 150-period 25-volt lighting system would be applicable to the roadways and haulage ways, but to my mind there appears to be some difficulty about its use. Of course it would be a complicated system of wiring, and one could not possibly transmit power at 25 volts to lamps a good distance away. It would mean the adoption of a system of transformers, and in addition, I suppose, with existing plants at 50 periods, the installation of one or more frequency-changers. A transformer has, I think, been mentioned, and brought to notice by Dr. A. Russell, which is a sort of frequency transformer in which the triple harmonic is utilized, in which case one could obtain 150 periods on a 50-period system. I should like to know if the author is in possession of any information in regard to such a transformer. The statement is made in the paper that direct current generally is unsuited to mining work. Can the author say what dangers are likely to be experienced from sparking commutators, and whether there is great danger from explosions taking place at slip-rings, because sparking does frequently occur at slip-rings on starting up? On one particular motor which I recently saw driving a haulage there were four brushes per spindle, and four spindles. Actually there was, on two spindles at all events, only one brush and in the other box three neatly-cut pieces of coal to act as brushes. This struck me as being rather dangerous. I should be glad if the author would say whether in his opinion there is a real danger of explosion from sparking in that case, or whether an explosion could only possibly occur in the event of, say, a complete flash-over.

Mr. W. H. N. James: The author mentions that the circuits from which he obtained ignition were, in certain cases, non-inductive. The term "non-inductive" must be taken in a relative sense and I should like to know if any tests have been made using circuits having different degrees of inductance. Another point is the use of the term "transient arc." Can the author give some idea of the duration of the arc covered by this expression and also say what influence the duration of the arc has on the minimum ignition current for a certain mixture? The phenomenon of ionization from a hot electrode after the arc has gone out can be very well shown with an ordinary 10-ampere d.c. carbon arc. If such an arc is blown out and the air current maintained for, say, 1 second, it will be found that the arc restarts immediately on the cessation of the air current. In regard to electrical endosmose, I think that the explanation given would have been clearer had it been mentioned that the water which takes part in the action must be positively electrified, and in this connection it may be noted that Mr. Evershed, in his paper on "The Characteristics of Insulation Resistance," * stated that water was strongly electro-positive to practically all insulating materials.

[The author's reply to this discussion will be found on page 509.]

* *Journal I.E.E.*, 1914, vol. 52, p. 51.

Scottish Centre, at Glasgow, 9 April, 1924.

Mr. S. Mavor: The author has been a pioneer in research into the phenomena of electric ignition, and the work upon which he has been engaged has very great economic as well as scientific and humane importance. He has had opportunities of investigating these phenomena under below-ground conditions and of examining the conditions in the mine after most of the serious colliery disasters in this country during recent years. The paper has appealed to me particularly in connection with the safe use of high-frequency current for underground lighting. The miner's safety-flame hand-lamp is deplorably inadequate as a means of illumination, and the miner normally works in semi-darkness. The electric hand-lamp has to a considerable extent improved the conditions, and the result of its use is to increase the miner's output by something like 10 per cent. We must go further than that, and the extremely interesting suggestion to use high-frequency current in order to make sparking innocuous opens up a new vista. The author refers specially to the importance of better lighting in the roadways. That, I think, though important, is secondary. At present the nodal points of haulage, at least in the intake airways, are fairly well lighted, but to my mind it is much more

important to have improved lighting at the working face. In these days of intensive mining, men are grouped in considerable numbers at a comparatively short length of face. This is a complete departure from the conditions in which men work individually or in pairs at considerable distances apart, and in which the use of individual lamps is unavoidable. Nowadays large outputs are got from short faces, and the illumination of these faces ought to be equal to the illumination of workshops on the surface where corresponding numbers of men are employed. Not only is the work greatly facilitated by adequate lighting but the safety of the men is greatly increased. There are several places in Scotland where conveyer faces are illuminated by lamps of 25 candle-power each, at intervals of 10 to 12 ft. To be appreciated the effect must be seen and compared with the usual conditions. Anyone who has been near the return end of a conveyer face where a dozen or more men are working with open-flame lamps knows how suffocating is the atmosphere and how low the visibility due to foul smoke. It is manifest that in abundant light and cleaner air the efficiency of labour must be greatly enhanced. In open-lamp pits the flood-lighting of conveyer faces not only is technically and economically feasible, but is with great advantage already practised. The maturing of the author's proposal will make available in safety-lamp pits also the immense advantage of flood-lighting of conveyer faces. I should like to refer for a moment to the author's very ingenious combination of an accumulator and a transformer in a miner's electric lamp. One limitation of the use of this device is that when the electric coal-cutter is stopped for adjustment the switch at the gate-end must be opened, and in such a case the transformer would be out of action; although the light from the battery would be available the superior light from the power circuit would be unobtainable at the time when it was most required.

Professor F. G. Baily: I am very interested in the account of endosmose, which I should like to hear very much more fully explained by the author. It throws considerable light on many of the difficulties which cable manufacturers must have experienced, and why cables last much longer than would be expected from experience in other cases. Cables with oiled paper were invented some years ago. Such cables were used in house installations, and some had lasted for 25 years although badly installed. On page 488 the author points out the very great effect of oxide. It seems to me that possibly if the surface is oxidized, and the arc is broken between the oxidized surfaces, the oxide will become rather more heated than the pure metal would be, the arc would break through the oxide and heat it in passage, and that heated oxide would be more capable of igniting the gas than would the metal, and would of course retain its heat longer. It is rather a different suggestion from the author's and I should like to hear his opinion of it.

Dr. S. Parker Smith: What I feel with regard to much of the flame-proof apparatus now available is that it is not properly used and cared for when underground. This doubtless results in many accidents. In consequence of such misuse or carelessness, the maker's effort becomes valueless. In response to requests, Prof. Burns and I are arranging a laboratory at the Royal Technical College for the testing of flame-proof apparatus. With regard to the breaking of the current, can the author tell us if the arc could be made less dangerous by having two switches in series as is done in certain classes of apparatus? The ideal would of course be to avoid the need of flame-proof apparatus by arranging that under no conditions whatever could an explosion occur.

Professor G. W. O. Howe: In connection with endosmose, I believe I am right in saying that in the conduit tramway system in London, where there are both positive and negative conductor rails in the conduit, the polarity is systematically changed over at regular periods, because the negative conductor gradually gets damper, whilst the positive becomes drier. When the change-over is made, the one that was wet gradually dries and the other one gets wet. I can say nothing from experience about the practical application of the appliances mentioned by the author, but I am very much interested in the scientific aspect of many of the problems put before us. The whole subject of ignition and explosion seems a great mystery and opens up an important field calling for further investigation and research of a fundamental character. The curves shown in Figs. 7 and 8 are particularly interesting. One would expect that as the frequency is increased the chances of explosion would grow less and less. I did not follow the author's explanation of the depression in the curves, and I should be very pleased if he could make it clear.

Mr. F. Anslow: It would be interesting to know how the author gets 160 periods from the ordinary coal-cutter supply, which is usually at 25 or 50 periods. It is well known that, under present conditions, electricity cannot be taken to certain places in a mine, but if the author's apparatus can be made satisfactory this regulation might be altered. In this connection I have recently had occasion to watch with particular interest the development of a special type of lamp. This is designed as a self-contained unit, operated by an air turbine driving a small generator, which is connected directly to the lamp contained in the same fitting. The periodicity is, I believe, somewhere in the neighbourhood of 400, and is thus well above the figure referred to by the author. The lamp can be connected to any compressed-air system underground, and can be used with perfect safety in places where electricity is not permitted.

The Author's Reply to the Discussion.

Professor W. M. Thornton (*in reply*): I entirely agree with Mr. Sparks that it is one of the most striking features of coal mining that accidents from causes which on investigation are found to be always present occur so seldom. There is a natural high factor of safety in mining operations, and if we could overcome

the mechanical risks due to falls of roof and on haulages, coal-mining would be much safer. I am glad to hear that Mr. Sparks does not look unfavourably on the proposal for improved lighting by low-voltage high-frequency current. This might well be tried in a mine where there is no gas, and the experience gained could then be applied to the case of fiery mines. If we are to eliminate horse haulage there must be better lighting on roads, for a horse can be stopped quickly where there is a slight fall or risk of damage, whereas mechanically hauled tubs cannot.

In reply to Mr. Nelson, my view of face lighting is that it can be done in two ways, by a fitting on or small extension from a coal-cutter to which supply is already made, or by a system similar to that now used by Mr. Mavor in non-fiery mines, the lamps being strung along a cable supported at the roof. This is found practicable, and satisfactory in the cases tried, and I believe that there will be no insuperable difficulty in extending it.

Mr. Horsley has himself suggested the remedy for those long-continued arcs which burn through insulation and when they occur are the most dangerous forms of open sparking. Automatic trip-gear has of recent years reached a high state of perfection and there should be no case where such gear is not applicable.

Mr. Melsom is right in regarding dry earth as an insulator, and it is for this reason that continuity of armouring to bank is now essential, but as most earths are at the surface and as for several feet down the earth is usually moist it is customary to regard contact to earth as dangerous both for shock and fault leakage. The earth plate shown requires watering once in several months in summer; in winter not at all. The truth is that earth currents are confined to a relatively thin layer on the surface of the ground. The order of resistance obtained from the earth plate is a fraction of an ohm under the best conditions. Mr. Higgs suggests that coke would be better than gravel for the fillings. This is only suggested as a top layer and personally I regard coke breeze as a bad thing near earth plates if it can be avoided. In regard to the influence of capacity and inductance I would refer Mr. Higgs to the list of papers given below at the end of my reply to the discussion. Capacity and inductance are of the first importance in such transient phenomena as those discussed in the paper, and in these experiments every precaution was taken to keep both of them below values which begin to have a perceptible effect on ignition.

I agree with Mr. Selvey that there are no risks in the use of electricity underground that cannot be remedied as soon as they are known. It was the object of the work described in the paper to explore ground which had not hitherto been examined, to find risks before a great disaster called attention to them. The apparatus that I have in mind to obtain high-frequency current is a Dykes transformer described on page 553 of Dr. Russell's "Theory of Alternating Currents." This four-core transformer enables a supply at any frequency to be superposed on a three-phase system for use wherever it is tapped by a similar transformer.

Mr. Hunt indicates a very wide field of investigation. The thing greatly desired is to generate electricity straight from coal without the intervention of the secondary thermal processes which accompany combustion. It is agreed that the first act in combustion is "activation" or ionization of the combining elements. This is an electrical process, and some further knowledge of the electrical phenomena accompanying combustion is to be desired. The curves in the paper show that the effect, though not simple, is regular.

Mr. Morgan raises the important point of the high voltage obtained on magneto instruments. If open sparking can occur on these they undoubtedly require to be examined, and as the armatures of such machines have a high inductance their use might prove to be risky even though the currents are small. As to earthing, I see no objection to having earth connections underground wherever possible in addition to the regulation earth at bank to which all cable sheaths are bonded. If the machines are (as is usual) star-connected it makes no difference whether the neutral point is earthed or not so far as circulating currents are concerned, but faults are more easily detected when it is earthed. It is not "putting a premium on breakdowns" to earth the neutral, but providing a path for leakage currents to the trip gear.

The system suggested by Mr. Myer is practically that used so largely in California for dust deposition, but dust is stirred up so often in a mine that no device would be practicable, nor could its insulation be maintained.

Mr. Midgley raises the question of ignition of coal dust by sparks. I think that with pulverized coal, as distinct from coal dust, there might be occluded gas released and accompanying the dust which would make the dust more inflammable, as indicated in Table 1. There is no doubt that electrostatic sparks can be obtained from clouds of dust of this kind, but not enough to ignite dust free from gas.

Mr. Dance has pointed out one of the great risks of enclosed machinery with divisions giving two distinct volumes. An explosion in one may, and does, raise the pressure in the other before its explosion, so that the resultant pressure is raised above the 110 lb. usually taken as a maximum. The maximum pressure is not proportional to the initial pressure. The relation can be written as follows: The ratio of pressure-rise equals unity plus the ratio of the rise of temperature in explosion to the temperature before ignition. This added ratio diminishes as the compression increases. There is no doubt that the modern lamp with a high-temperature filament ignites gas more readily than one with lower temperature. This has been shown by researches by Clark and Ilsley at the Bureau of Mines, U.S.A. (Bulletin No. 131).

Mr. Morton is, I venture to think, making a not uncommon mistake when he suggests that a trip gear at a distance may operate less quickly than it would if near by. It is not easy to realize that electrical action due to a fault or break of cable is almost instantaneous—certainly within 1/200 000 sec.—over any mine system. I am not in favour of bitumen cable except for alternating current and under conditions where the rise of temperature is small.

I would refer Mr. Bolton Shaw to a paper on "The Ignition of Gases by Hot Wires" (see the end of my

reply) for an answer to his question as to the influence of diameter of filament on ignition. Metal-to-metal sparks are, I believe, less dangerous than those between metal and stone, but I have not made experiments on this myself. The first earth plate made on the lines of Fig. 10 was of galvanized cast iron. It was substantial but unduly heavy for the work, and later ones were of $\frac{1}{16}$ in. galvanized iron. How long they will last remains to be seen. They will carry very large currents.

Mr. Vernier has most convincingly stated the case of alternating versus direct current on cables, and since this is, after all, the part of the electric system in mines where risk is most likely to occur at the present time with flame-proof gear coming into general use, his opinion must carry great weight with mining engineers.

The curious case mentioned by Mr. Fisher of bells being burnt out is, I think, one of what was called in the war "earth induction." The stray currents between two earthed points carrying a heavy short-circuit on the surface might well spread, or even be led by shaft lining and rails, so as to give a destructive gradient even at 120 fathoms. Mr. Fisher's experiments are very interesting. I venture to think an arc of 50 amperes or so sustained for several seconds on a 3 000-volt line might have the nature of an explosion, but this rarely occurs in a confined space. The danger from sparking at haulage ropes, due to imperfect earthing, is at least as great as that from bells in the old days.

In reply to Mr. Schuil, the pressure is between 100 and 110 lb./sq. in. when the initial pressure is atmospheric. Dr. Wheeler's recent experiments on the cooling produced by flanges confirm in every way the development of flame-proof gear by simple machined flanges first developed by Mr. Schuil for Messrs. Reyrolle & Co.

The point raised by Mr. Grover is, I take it, this: The gas in such percentages is not inflammable and is therefore not the first source of the explosion. The dust is ignited as before by arcs though not by sparks, but, when it begins to burn, the air around each particle containing gas feeds the flame exactly as gas feeds the flame in a safety lamp.

I am glad to have Prof. Poole's approval of the lamps shown, and of the suggestion to obtain more light. No one knows better than he the conditions under which coal-mining operations are carried out, and the necessity for continued investigation. As requested, I have added, at the end of my reply, a list of the papers which more or less led up to this. An electric safety lamp has been devised which will indicate the presence of pit gas, but it is not at present sufficiently robust for use in a pit. It indicates about $2\frac{1}{2}$ per cent of gas in a few seconds.

In reply to Mr. Anderson, no one appreciates more than myself the value of the work done at Eskmeals by the Mines Department. My point is that, apart from the research work proper, there are from time to time large-scale demonstrations arranged which seem to me to be designed to bring home to mining men, who might not otherwise realize the magnitude of the points at issue, the great dangers which may arise from ignited coal dust. With regard to concentric mains, which should be prohibited, I fully agree that the best solution in dealing with such systems is to carry the connection to the motor from a gate-end switch by a three-core truly flexible cable—not a stiff and unwieldy semi-flexible concentric trailer. The best way to deal with hollow fittings which may "breathe" is, in my opinion, to make the safety outer covers fit as closely as possible to the protected part and so have a small volume of inflammable gas. With such small spaces a flange with $\frac{1}{2}$ in. to $\frac{3}{4}$ in. would be safe. The cases of sparking mentioned by Mr. Anderson show the necessity for a common-sense revision of some of our special rules.

In reply to Mr. Bolton Shaw, the curves of Fig. 9 will be understood if it is noticed that at voltages of 50 and less the lines go up very steeply; they become in effect straight. Fig. 9 is the result of separate and much more difficult experiments. It is not easy to control by flexible leads currents of hundreds of amperes attached to moving contacts, nor is it easy to repeat the work in the presence of coal dust, though it will have to be done before the suggested scheme of lighting is approved. I am glad to hear that the cost is not likely to prove prohibitive. The frequency-changer I have already dealt with in my reply. The system of wiring proposed at the face is by contact blocks with short leads to the plug, or switch contacts on coal-cutters. This will not interfere with movement behind the coal-cutters and, as Mr. Bolton Shaw remarks, the small added inconvenience of such leads would be more than balanced by the gain of safe illumination.

In reply to Mr. Lee, I think that another paper must be written dealing with the proposed means of face lighting. This is rather beyond the scope of the present paper. There is no objection to bare-wire signalling on battery-bell circuits if the bells are provided with shunts or sleeves or parallel windings to suppress inductance sparks. The earth plate is made $\frac{1}{16}$ in. thick because greater thicknesses are not necessary for the purpose of earthing.

The point raised by Mr. Buchanan is interesting. I have shown elsewhere that ignition is not proportional to the power of an arc. The fact that lower-voltage circuits have, as a rule, lower impedances is in their favour. Inductance always makes ignition easier.

I welcome Mr. Corlett's valuable criticism. He is right in assuming that the suggestion to use a higher frequency applies to lighting alone. I do not believe that there would be any marked gain in safety for machines. By mechanical accidents I mean those not directly electrical, such as by shock or explosion. I should be the last to derive a general conclusion from one experiment, and that on the breaking of a cable by a wedge is only given as a single instance of a test made for a purpose. Mr. Corlett says that gas frequently comes into a place without warning. There is then the greater reason for the use of warning lamps such as those shown. As to the flame from a heavy short-circuit inside a switchbox, I have known the cover of an enclosed switch of the old wall type in a mine to be blown from its bolts and shattered by a short-circuit in a haulage house a long way from bank. In such cases there is nearly always a prolonged arc and heating of the metal. The system of frequency transformation

advocated previously would do much to make the difficult case mentioned by Mr. Corlett a more economical proposition rather than the motor-generators, frequency-changers and the double system of wiring, which is not necessary on the Dykes scheme.

In reply to Dr. Garrard, my view of chemical action from the physical side is that, since all atoms are electrical, chemical combination must start by a change of electrical conditions—probably in the valency electrons at their surfaces. Catalytic action is, in my opinion, only another name for ionic effects, which do not themselves involve molecular change in the ionizer. The electrical methods which have been devised for the indication of gas in pits are unfortunately not in common use. They are capable of great sensitiveness, but are rather delicate and bulky as at present made. It is necessary to make use simultaneously of all methods for preventing open sparking or for lessening its danger. If this is done very complete protection is obtained.

Mr. Angold is right in assuming the speed of break to be that usually met in an accident—a fairly rapid separation of contact. What may be called "scraping contacts," i.e. slowly separated surfaces scraping at the points of separation, are the worst cases, but no two can be made alike. For the purpose of comparison of the influence of the various electrical factors which had not been previously known, a break was chosen which is a simple separation, without scraping, of current-carrying poles.

I do not think that Prof. Cramp is right in assuming that the discharges were oscillatory. There is no evidence of high-frequency oscillation in any of the many oscillograms taken of these sparks. In one case special search-coils were wound around a cable for the purpose of examining whether such oscillations were present. This is referred to in section (9) of the paper. Prof. Cramp will find at the end of my reply, papers, especially the earlier ones, in which the various points he raises were examined, e.g. size and material of poles. One point of interest is that the least smear of mercury on the surface of a contact greatly increases the risk of ignition. The thermal theory does not account for this.

Mr. Wilson is right in his view that the cable on a direct-current system which gives way from moisture is always the negative. I agree with him that the actual tests of flame-proof gear, though beyond the scope of this paper, should be made with plenty of power behind the electrical circuit. His observations of the relief methods in such gear are most interesting.

In reply to Mr. Forrest, several severe accidents have occurred due to flame and arc ignition of dust in coal bunkers or on screens at collieries, and the U.S.A. Bureau of Mines has recently issued a report on the ignition of pulverized coal by transient arcs in which the conclusions reached in the first of the list of papers at the end of my reply are substantiated. As a rule the dust cloud must be very dense at the point of ignition, more so than in an extended explosion.

Mr. Wood is correct in taking the limit to be that which when the current is alternating will not fire the mixture however slowly (within reason) the poles are separated. In answer to his first question I would say that, provided there is a time-constant of the order of 1/1 000 sec., the circuit is safe. The reactance of a circuit is not at all a good means of limiting the current in these timing cases; a buffer resistance is much better.

Mr. Orsettich is correct in contending that at present there is a margin of interpretation of the special rules for the use of electricity in mines. Gas cannot be excluded from machines, but the tendency at the present time is not to encourage the use of high-powered machines where there is possibility of gas occurring. Relief valves are a convenient means of dealing with an established ignition. The object of the paper was to find the limits of ignition.

In reply to Mr. Harvey, the materials of the poles have influence on break sparks but not on jump sparks. Bells with shunted windings have been running now for a good many years and on inspection show no signs of loose contacts. One might as well say that bells should not be used at all because their windings might break; one knows from experience that they do not. I doubt whether thermionic valve relays will come into common use below ground in mining, but the idea is most interesting. The drop in the curve of Fig. 7 is not due to electrical resonance; it was obtained from a number of different machines with presumably different electrostatic capacities, though these were not measured, but the conclusive argument that it is not electric resonance is that the curve reverts with remarkable suddenness to the original values continued. The practicability of face lighting is not a question of theory. It has been proved by Mr. Mavor, and instead of 8-c.p. lamps "certainly causing a glare injurious to sight" the reverse is found to be true.

Mr. Wadeson touches one of the most difficult points in the use of electricity in mines, viz. the gradual replacement of obsolete machinery on systems. The general consensus of opinion, apart from research, is that alternating current gives less trouble in mines and is altogether more convenient except where fine speed-control is necessary. A system of signalling transformers can be made safe by the use of non-inductive shunts of fairly high resistance at regularly spaced points along the line. To lessen the risk of faults between windings, an earth shield could be made to trip the primary circuit before the low-pressure side was affected.

Mr. Holiday does not like the electric warning lamp, and I agree that there would have to be a special lamp cabin and special treatment would have to be taught. But one of the other types shown would not meet with the objection of fragility. If these lamps come into use it will probably be found that the extinguisher type will be liked best and that the electric-warning type will be kept for use in places which require special watching when men are not present, as Mr. Moss asks. The bell for warning would of course be semi-permanent, at a gate-end for example. I am sorry that I am unable to quote a case of the installation of the high-frequency system or of the special lamp bases, but the Mavor and Coulson system has many features in common—flood lighting at the face, for example—and the higher frequency could well be tested under appropriate conditions in a naked-light mine to obtain figures as to reliability and convenience. The proposal is too recent for such

a scheme to have been carried into practice. Several inquiries have been made, but the mines all have gas and the Mines Department has not yet been approached in the matter.

In reply to Mr. Walford, alternating-current signalling is in use but requires safeguards due to the inductance of the circuits. The present position is that bare-wire a.c. signalling is not regarded as satisfactory.

The transformer referred to by Mr. Jenkins is that mentioned in my reply to Mr. Selvey. Both commutator sparking and slip-ring sparking come within the danger limit of the currents examined; the only thing to do with such apparatus is to enclose it.

The transient arcs mentioned by Mr. James have a duration of from 0·002 to 0·02 sec., depending on the voltage. The case he mentions of low-voltage arcs striking across a gap between hot carbons which would require when cold several thousand volts, is a decisive indication of the intense ionic activity in gases near red-hot poles. Water in endosmose behaves as if positively electrified, that is, the whole stream begins to move as soon as the field is applied.

I am very glad to have Mr. Mavor's approval of the low-voltage high-frequency scheme of underground lighting. No one has done more than he for the improvement of colliery lighting, especially at the face, and all the advantages he claimed in cleanliness of air and efficiency of labour are undoubted. My suggestion to use the coal-cutter as the point of attachment was to save running lighting cables from the gate end, but if a marked advantage were obtained from the use of separate cables I have no doubt they would soon be adopted.

Prof. Baily's suggestion that the oxide might act as an accelerator, by reason of its higher resistance or temperature, must be considered. A thick film would undoubtedly have the effect which he indicates, but adsorbed oxygen would not, I think, lead to a measurably higher temperature at the point of break of circuit.

In reply to Dr. Smith, I am strongly of opinion that electrical machinery underground requires more inspection and general supervision than is commonly given to it. There is almost more in maintenance than in design. Two switches in series should be equivalent to halving the voltage-rise at the end, and this would help, though all power circuit-breakers are best kept within flame-proof covers.

Prof. Howe calls attention to Fig. 7 and asks for a further explanation. I regard the drop in the curve as due to ignition of the gas by the hot metal exposed after the arc has been cut off and before the hot spot where the arc has been has cooled down, as it does very rapidly. Ignition by white-hot metal, is, I believe, easier than by the surface of a flame of the same temperature and area. As the frequency is raised, the current first has to be increased to reach the critical temperature of thermionic discharge activation and ignition while the arc lasts. The time of duration of each arc is inversely proportional to the frequency; and at the higher frequencies the faster the arc is shut off the quicker is the access of the gas to the white-hot metal, and the more easily ignition occurs. Here are clearly the conditions for a maximum. The argument that it is ignition from the hot metal that causes the dip is that as the frequency is raised, the igniting current falling in value should begin to fail to heat the metal to the limit of thermionic discharge to cause ignition in the time of one quarter-period (the greatest duration of an arc), as in fact it does. It is well known that thermionic discharge fails with startling suddenness as the temperature is lowered, and I regard the necessity to increase suddenly to high values at a frequency of 380 the current required for ignition as due to this failure of the thermionic discharge.

Mr. Anslow's query as to frequency I have answered earlier. The compressed-air electric lamp is a most interesting development, and I should much like to see one. If the voltage at break of the inductive generator circuit exceeds 25, i.e. the arcing voltage, there may be risk of ignition. It would be interesting to examine such a lamp as a source of ignition.

Papers by the Author on Ignition of Gases.

(See discussion at Newcastle, page 497.)

W. M. Thornton and E. Bowden: "The Ignition of Coal Dust by Single Electric Flashes," *Transactions of the Institution of Mining Engineers*, 1910, vol. 39, pt. 2, p. 1.

W. M. Thornton: "The Ignition of Coal Gas and Methane by Single Electric Arcs," *ibid.*, 1912, vol. 44, pt. 1, p. 145.

—— "The Comparative Inflammability of Mixtures of Pit Gas and Air ignited by Momentary Electric Arcs," *ibid.*, 1913, vol. 46, pt. 2, p. 112.

—— "The Influence of the Presence of Gas on the Inflammability of Coal Dust and Air," *Colliery Guardian*, 19th September, 1913.

W. M. Thornton and J. A. Smythe: "A Case of Gaseous Explosion caused by the Electric Heating of Bitumen in Cable Troughs," *Electrician*, 1913, vol. 71, p. 820.

W. M. Thornton: "The Limiting Conditions for the Safe Use of Electricity in Coal Mining," *Electrician*, 1914, vol. 73, p. 822.

—— "The Electrical Ignition of Gaseous Mixtures," *Proceedings of the Royal Society*, A, 1914, vol. 90, p. 272.

—— "The Ignition of Gases by Condenser Discharge Sparks," *ibid.*, 1914, vol. 91, p. 17.

—— "The Least Energy required to start a Gaseous Explosion," *Philosophical Magazine*, 1914, ser. 6, vol. 28, p. 734.

—— "The Lost Pressure in Gaseous Explosions," *ibid.*, 1914, ser. 6, vol. 28, p. 18.

—— "A New Battery Signalling Bell," *Transactions of the Institution of Mining Engineers*, 1915, vol. 50, pt. 1, p. 19.

—— "The Reaction between Gas and Pole in the Electrical Ignition of Gaseous Mixtures," *Proceedings of the Royal Society*, A, 1915, vol. 92, p. 9.

W. M. Thornton and R. V. Wheeler: Home Office Report on "Electric Signalling with Bare Wires so far as regards the Danger of Ignition of Inflammable Gaseous Mixtures by the Break Flash at the Signal Wires." [1916].

W. M. Thornton: "The Total Radiation from Gaseous Explosions," *Philosophical Magazine*, 1915, ser. 6, vol. 30, p. 383.

W. M. THORNTON: "The Ignition of Gases by Impulsive Electric Discharge," *Proceedings of the Royal Society*, A, 1915, vol. 92, p. 381.

—— "The Influence of Pressure on the Electrical Ignition of Methane," *Electrician*, 1916, vol. 77, p. 775.

—— "The Limits of Inflammability of Gaseous Mixtures," *Philosophical Magazine*, 1917, ser. 6, vol. 33, p. 190.

W. M. THORNTON: "The Ignition of Gases by Hot Wires," *ibid.*, 1919, ser. 6, vol. 38, p. 613.

—— "The Ignition of Gases at Reduced Pressures by Impulsive Electric Sparks," *ibid.*, 1920, ser. 6, vol. 40, p. 345.

—— "The Principles of Electrical Ignition," *Beama*, 1922, vol. 11, p. 524.

PROCEEDINGS OF THE INSTITUTION.

SPECIAL GENERAL MEETING OF CORPORATE MEMBERS, 28 FEBRUARY, 1924.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 5.30 p.m.

The notice convening the meeting was taken as read.

The following Resolution was proposed by the President :—

"That the following be substituted for Bye-law 9 of the Bye-laws of the Institution :—

"9. (*a*) An Honorary Member shall be entitled to the exclusive use after his name of the initials 'Hon. M.I.E.E.'; a Member of the initials 'M.I.E.E.'; an Associate Member of the initials 'A.M.I.E.E.'; an Associate of the initials 'Associate I.E.E.'; a Graduate of the initials 'Graduate I.E.E.'; and a Student of the initials 'Student I.E.E.'

"(*b*) Every Member and Associate Member is, and is entitled to describe himself as, a Chartered Electrical Engineer, and in using that description after his name shall place it after the designation of the class in the Institution to which he belongs, stated in accordance with the following abbreviated forms, namely, M.I.E.E. or A.M.I.E.E., as the case may be.

"(*c*) A Member or Associate Member practising

(i) under the title of, or as an officer or employee of, a Limited Company authorized to carry on the business of an electrical engineer in all or any of its branches, or

(ii) in partnership with any person who is not a Member or Associate Member of the Institution under the title of a Firm

shall not use or permit to be used after the title of any such Company or Firm the designation 'Chartered Electrical Engineer' or 'Chartered Electrical Engineers' or describe or permit the description of such Company or Firm in any way as 'Chartered Electrical Engineer' or 'Chartered Electrical Engineers.'

"(*d*) No person shall adopt or describe himself by any other description or abbreviation to indicate the class to which he belongs than is provided in this Bye-law for such class."

The Resolution, after being seconded by Sir James Devonshire, K.B.E., was carried unanimously, and the meeting terminated at 5.50 p.m.

712TH ORDINARY MEETING, 28 FEBRUARY, 1924.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

On the motion of Sir James Devonshire, K.B.E., seconded by Mr. R. T. Smith, a hearty vote of congratulation was accorded the President on his nomination for a Fellowship of the Royal Society of London.

The minutes of the Ordinary Meeting of the 14th February, 1924, were taken as read and were confirmed and signed. A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A list of donations to the Benevolent Fund (see pages 299–300) was taken as read and the thanks of the meeting were accorded to the donors.

A paper by Mr. A. S. FitzGerald, Associate Member, entitled "The Design of Apparatus for the Protection of Alternating-Current Circuits" (see page 561), was read and discussed.

On the motion of the President a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.50 p.m.

37TH MEETING OF THE WIRELESS SECTION, 5 MARCH, 1924.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 6th February, 1924, were taken as read and were confirmed and signed.

A paper by Commander J. A. Slee, C.B.E., R.N. (Ret.), Member, entitled "Development of the Bellini-Tosi System of Direction-Finding in the British Mercantile Marine" (see page 543), was read and discussed.

On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 8 p.m.

713TH ORDINARY MEETING, 6 MARCH, 1924.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 28th February, 1924, were taken as read and were confirmed and signed.

Messrs. H. Jenkins and S. F. Hill were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows:—

ELECTIONS.

Associate Members.

Barnett, Cecil John.
Edes, Noel Hamilton, Lieut., R.C.S.
Finnis, Arthur Hornsby.
Richardson, Samuel Sumner, D.Sc.
Smith, Sydney Luke.

Graduates.

Akehurst, Arthur Gerald.
Cadman, Norman.
Clark, Ernest Cameron.
Devine, James Joseph.
Graham, Eric Edward.
Guilford, Alfred Leslie, B.Sc.Tech.
Holdsworth, John Evelyn.
Nunn, Charles.

Students.

Addison, James Donald.
Alford, Frederick Albert H.
Allan, Robert Hector.
Angus, James Houston.
Ashworth, Graham.
Barnes, Richard Wynne.
Bates, Albert Edward.
Beck, Arthur Cecil.
Bedingfield, William King.
Benham, Cedric Minett.
Bentley, John.
Berindei, Matei.
Bhavnani, Hashmatrai Khubchand, B.Sc.
Bishop, Geoffrey.
Botcharsky, Constantin.
Bramley, John Henry.
Brownlie, James Millar.
Bryan, Leslie William.
Caley, Leonard Percy.
Chase, John Joseph.
Clifford, Albert Edward.
Connelly, Thomas Maurice.
Cornish, Henry Edmund.
Cox, Arthur Gerald.
Crake, Wilfred St. Maur E.
Crisp, John William.
Darby, William Joseph J.
D'Cruz, Cyril.
Douglas, Thomas Kenneth A.
Ferlie, George Balfour.
Firth, Allan Mitchell.
Fischer-Webb, Denis.
Flett, Robert Garrioch.
Foster, Horace George.
Froggatt, Arthur.
Fryer, Ronald Waring.
Gardiner, Herbert William B., B.Sc.(Eng.).
Gray, Albert Hilliard, M.Sc.
Gurney, William Albert J.
Hawkins, John Mortimer.
Heron, Thomas.
Hughes, Leslie Ernest C.

Students—continued.

Humphriss, Eric Allan.
Jelly, William Edwin.
Jervis, Walter, Junr.
Jones, Reginald Ernest.
Kay, Dudley.
Kelly, William.
Krestovnikoff, Igor.
Lappin, Henry.
Leman, Hugh Spence.
Mackenzie, Ian.
Mahajan, Lochan Singh.
Meers, Richard Adney.
Middleton, Alex.
Milner, Ewart Guy.
Minchin, Cecil William H.
Moes, Gerlacus.
Mudford, Francis Edwin.
Murray, George Andrew.
Northcote, John Wilfrid S.
Pearce, Fred Esmond.
Penny, John Carlton.
Phelps, John Lecky.
Plumbly, Richard William.
Rendle, Patrick Russel.
Sabikhi, Nihal Chand.
Short, Harry Redfern.
Sinclair, Ernest Morgan.
Spurr, Samuel Didsbury W.
Sykes, Herbert Archibald.
Taggart, John Douglas.
Takla, Fawzy.
Thomas, Ernest.
Weston, Harold Norman.
Wilkinson, Frank.
Wilson, William Frederick.
Woolgar, Leslie Vincent.
Young, Frank.

Associate.

Nash, Sir Philip A. M., K.C.M.G., C.B.

TRANSFERS.

Associate Member to Member.

Davey, Frank William.
Pearce, James George, B.Sc.
Skeates, Conrad Clemmans.
Stewart, Charles Lionel E.

Graduate to Associate Member.

Cairns, Archibald McFarlane, Capt. R. E., B.Sc.(Eng.).
Noor-el-Deen, Youssef.

Student to Associate Member.

Devonald, Norman.
Rose, Victor.
Spilsbury, Robert Samuel J.
Underwood, Cyril Lancelot.

Associate to Associate Member.

Nicol, Edward Watson L.

Student to Graduate.

Bellamy-Law, John William.
Bonny, Arthur George A.
Calder, John Maxwell.
Colquhoun, James Browne.
Conly, William Peter, B.Sc.(Eng.).
Datta, Narendra.
de Steiger, Frederick Bernard.

Student to Graduate—continued.

Dunlop, Robert Paterson.
Jackson, Horace.
Jones, Arthur Thomas.
Maguire, Austin Joseph (B.Eng.).
Morgan, Ivor.
Pound, Edwin Thomas.
Sheppard, Maurice William.
Smart, Henry Prescott.
Thompson, George.
Williams, Charles Branton.

A paper by Messrs. P. E. Erikson, Member, and R. A. Mack, Associate Member, entitled "Transmission Maintenance of Telephone Systems," was read and discussed.

On the motion of the President a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 7.45 p.m.

714TH ORDINARY MEETING, 20 MARCH, 1924.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 6th March, 1924, were taken as read and were confirmed and signed.

A lecture (with demonstrations) entitled "The Nature and Reproduction of Speech Sounds (Vowels)" was delivered by Sir Richard Paget, Bart.

On the motion of the President a vote of thanks to the lecturer was carried with acclamation, and the meeting terminated at 7 p.m.

715TH ORDINARY MEETING, 27 MARCH, 1924.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 20th March, 1924, were taken as read and were confirmed and signed.

A list of candidates for election and transferred approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A list of donations to the Benevolent Fund (see page 381), was taken as read and the thanks of the meeting were accorded to the donors.

The President announced that a portrait in oils of the late Willoughby Smith (President 1883) had been presented to the Institution by his sons, Mr. W. O. Smith and Mr. W. S. Smith, and the thanks of the meeting were accorded to the donors.

The President read an Order received from the Lords of the Privy Council, allowing the new Bye-law No. 9 (see page 381).

A paper by Lieut.-Col. H. E. O'Brien, D.S.O., Member, entitled "The Future of Main-Line Electrification on British Railways," was read and discussed. On the motion of the President a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.45 p.m.

38TH MEETING OF THE WIRELESS SECTION, 2 APRIL, 1924.

(Held in the Institution Lecture Theatre.)

Mr. C. C. Paterson, O.B.E., took the chair at 6 p.m., in the unavoidable absence of Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section.

The minutes of the meeting of the Wireless Section held on the 5th March, 1924, were taken as read and were confirmed and signed.

A paper by the Research Staff of The General Electric Co., Ltd., presented by Messrs. M. Thompson and A. C. Bartlett and entitled "Thermionic Valves with Dull-Emitting Filaments," was read and discussed.

On the motion of the Chairman a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 7.20 p.m.

THE DETERMINATION OF RESONANT FREQUENCIES AND DECAY FACTORS.*

By Professor E. MALLETT, M.Sc., Member.

(*Paper first received 26th September, and in final form 31st December, 1923.*)

SUMMARY.

Simple resonance curves plotted vectorically are approximately circular in form. The paper shows how the circle can be derived from the ordinary resonance curve by a simple graphical construction, and how from the derived circle and the original resonance curve a straight line can be drawn from which the resonance frequency and the damping are at once determined.

The constructions developed are explained by their application to telephone-receiver impedances and to electrical circuits.

TABLE OF CONTENTS.

1. SYMBOLS USED IN THE PAPER.

Z = modulus or size of total impedance of telephone receiver.
ψ = angle of impedance of telephone receiver.

Z_d = size of receiver impedance with diaphragm damped.
θ = angle of receiver impedance with diaphragm damped.

Z_r = size of receiver impedance due to motion of diaphragm.
χ = angle of receiver impedance due to motion of diaphragm.

A = size of force factor.
β = angle of force factor. (Defined by expression: Pull on diaphragm = $A|\underline{\beta} i$.)

z = size of mechanical impedance of diaphragm.
α = angle of mechanical impedance of diaphragm.

r = mechanical resistance of diaphragm.
m = equivalent mass of diaphragm.
s = stiffness coefficient (restoring force per unit deflection).
$Z' = Z/Z_d$ = ratio of the sizes of the impedances with the diaphragm free and damped respectively.
Δ = decay factor = $r/(2m)$.
i = current into receiver with diaphragm free.
i_d = current into receiver with diaphragm damped.
e = voltage across receiver (kept constant).
f = frequency.
f_0 = resonant frequency.

2. INTRODUCTION.

In a paper* by Professor J. T. MacGregor-Morris and the present author in which the ratio of the frequencies of some of the higher modes of vibration to that of the fundamental mode was measured, a difficulty arose in determining the exact value of the latter in the absence of a sand picture and of a sharply defined maximum sound. A rough solution only was obtained by drawing the curve of Fig. 1, which shows the current, i, in the receiver plotted against the frequency, f, and taking as the resonant frequency the point where the curve AB crosses the dotted line (obtained with the diaphragm prevented from vibrating).

If apparatus for setting up an alternating-current bridge had been available, the method described † by A. E. Kennelly and G. W. Pierce could have been used.

In this method, impedance measurements (in the form $A + jB$) of the telephone receiver are made, first with the diaphragm free and then with the diaphragm damped, and it is found that the vector difference of the two plotted vectorially has a circular locus. Resonance occurs at the diameter of the circle through the origin, and the damping is determined from the frequencies at the ends of the diameter at right angles. The theory of the telephone receiver is developed in a

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

* *Journal I.E.E.*, 1923, vol. 61, p. 1134.
† "The Impedance of Telephone Receivers as affected by the Motion of their Diaphragms," *Proceedings of the American Academy of Arts and Sciences*, 1912, vol. 48, p. 111.

series of papers by Kennelly and his various co-workers,* and this is used in what follows.

The present paper arose out of the desire to avoid bridge methods, which demand expensive apparatus and somewhat laborious calculations, and if possible to use a curve similar to that of Fig. 1, that is, drawn from current measurements without any knowledge of phase angles, to obtain the information required as to the resonant frequency and the damping. It was thought

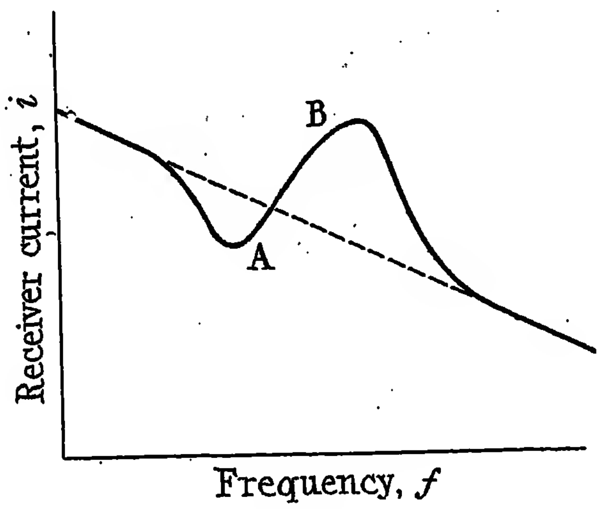


FIG. 1.

that if such a method could be established it would be especially useful at higher and perhaps quite high frequencies, where bridge methods are extremely difficult.

3. Outline of Theory.

By impressing a constant voltage v of known and variable frequency on the terminals of a receiver, and measuring the resulting current i, the size Z of the

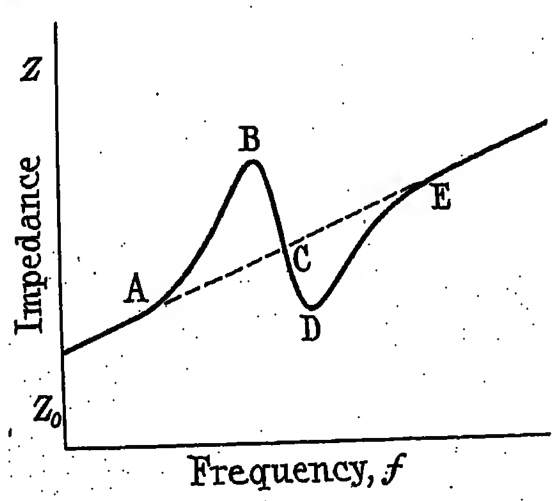


FIG. 2.

impedance of the receiver is determined as the ratio v/i, but not its phase angle. A curve similar to ABCDE of Fig. 2 is obtained on plotting Z against the frequency. If the diaphragm were prevented from vibrating the curve would be ACE, and from many experimental results it appears that over the range AE this curve is approximately a straight line.† Moreover, it is found that the angle of the impedance represented by ACE is approximately constant over this range, so that the impedance with the diaphragm damped (or in the absence of the resonance) may be written $Z_d|\underline{\theta} = (Z_0 + \omega Z_1)|\underline{\theta}$, where Z_0 is the intercept of the line ECA on the OZ axis, Z_1 is the slope of the line, and θ is the constant angle of the impedance. The total impedance of the receiver with the diaphragm

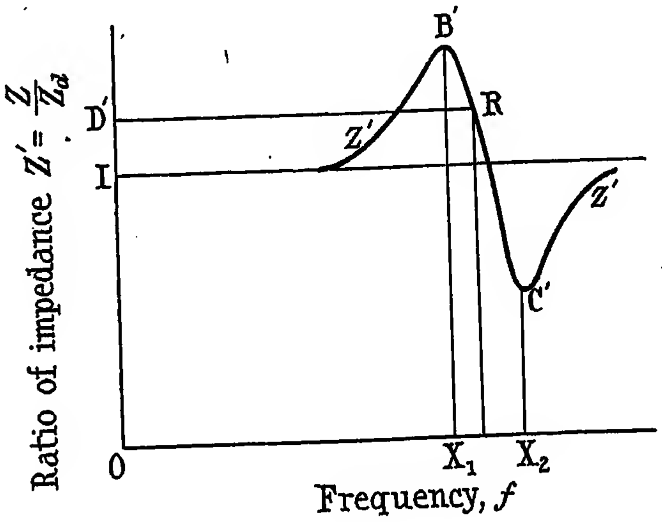


FIG. 3.

free to vibrate may be written $Z|\underline{\psi} = Z_d|\underline{\theta} + Z_r|\underline{\chi}$, where $Z_r|\underline{\chi}$ is that part of the impedance which is due to the motion of the diaphragm. This Kennelly has shown to be

$$Z_r|\underline{\chi} = \frac{A^2}{z}\,\overline{|2\beta + \alpha}$$

where A is the force factor and $|\underline{\beta}$ its angle, and $z|\underline{\alpha}$ is the mechanical impedance of the diaphragm, given by

$$z|\underline{\alpha} = r + j\left(m\omega - \frac{s}{\omega}\right) \quad . \quad . \quad . \quad . \quad (1)$$

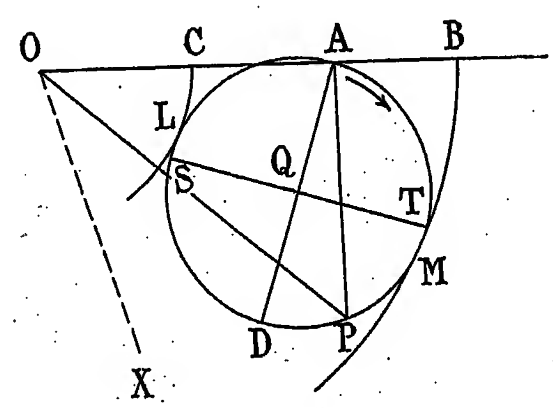


FIG. 4.

where r = total equivalent mechanical resistance of the diaphragm, and is of the form $r_1 + \omega r_2$; m is the equivalent mass and s the stiffness coefficient, both very nearly independent of the frequency.*

So we may write for the total impedance of the telephone receiver

$$Z|\underline{\psi} = Z_d|\underline{\theta} + \frac{A^2}{z}\,\overline{|2\beta + \alpha}$$

* A summary appears in the *Post Office Electrical Engineers' Journal*, 1923, vol. 16, pt. 2, p. 144. A complete account is given in a recently published book on "Electrical Vibration Instruments," by A. E. Kennelly.

† A. E. Kennelly and H. A. Affel: "The Mechanics of Telephone-Receiver Diaphragms, as derived from their Motional-Impedance Circles," *Proceedings of the American Academy of Arts and Sciences*, 1915, vol. 51, p. 419.

* See A. E. Kennelly and H. Nukiyama, *Transactions of the American Institute of Electrical Engineers*, 1919, vol. 38, pt. 1, p. 419.

of which we have measured Z, and can either infer Z_d by covering a sufficient frequency-range with the Z measurements, or measure it directly by damping the diaphragm. We have, however, no knowledge of the angles.

Dividing throughout by $Z_d\underline{|\theta}$ we obtain

$$\frac{Z}{Z_d}\underline{|\psi - \theta} = 1 + \frac{A^2}{Z_d{}^2}\overline{|2\beta + \alpha + \theta} \quad . \quad . \quad (2)$$

This expression gives the key to the method. Find the ratio $Z/Z_d = Z'$ for various frequencies, and draw in the direction AMDLA. Z' is, by construction, a maximum at OM and a minimum at OL, and resonance occurs approximately at the diameter AD. The frequency at which resonance occurs is ascertained by finding the corresponding point on Fig. 3. Set up OD′ in Fig. 3 equal to QD in Fig. 4, and draw a horizontal through D′ to meet the B′C′ curve in R. Then D′R is a measure of the resonant frequency.

It is clear also that the angle BAD is equal to $2\beta + \theta$, while the angle DAP is α and the angle AOP is $\psi - \theta$. To convert Fig. 4 to an actual impedance diagram of the receiver, it would be necessary to draw

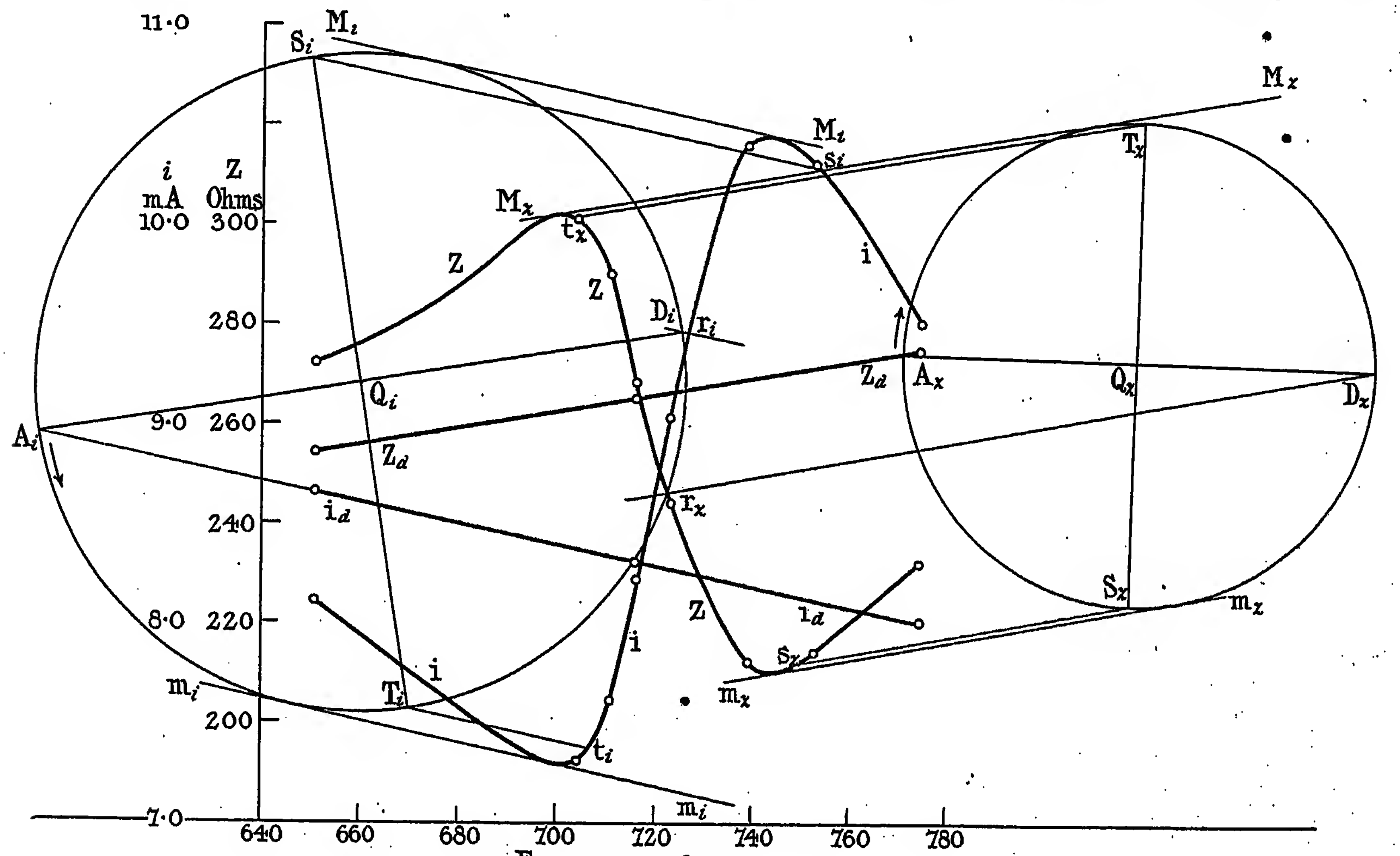


FIG. 5.

a new curve (Fig. 3) of Z' against f. The ordinates are seen from Equation 2 to be the size of the vector sum of unity and $\frac{A^2}{Z_d{}^2}\overline{|2\beta + \alpha + \theta}$. This last expression has, at any rate for frequencies not far removed from resonance, very nearly a circular locus, as the alterations of Z_d are small compared with those of z. So to construct the vector diagram from which Fig. 3 may be derived, we set off in Fig. 4 OA = unity (OI of Fig. 3), OB = the maximum ordinate X_1B' of Fig. 3, and OC = the minimum ordinate X_2C'. With O as centre and OC, OB as radii draw arcs CL and BM. Draw a circle to touch these arcs at L and M and to pass through the point A. Let the centre of this circle be Q and its diameter through A be AQD. Then the right-hand side of Equation (2) is given by OP, where OP is any vector drawn from O to meet the circle in P. As the frequency increases from a low value the point P starts from A and describes the circle a line OX so that the angle XOA $= \theta$, to give the new reference line, and to multiply each vector OP by the corresponding value of Z_d.

From the circle AMPLA the value of $\Delta = r/2m$, the decay factor, can be found. Draw a diameter at right angles to AD, cutting the circle in T and S. Find the corresponding points T′ and S′ in Fig. 3 and hence the frequencies f_t and f_s at which the values of α are $+ 45°$ and $- 45°$ respectively. Then $\Delta = \pi(f_s - f_t)$. A better method not depending on two points alone is developed later, however, in showing how far the assumptions made above are justified in an actual case.

4. Application of the Method to Some Actual Measurements.

The method thus arrived at will now be applied to some actual measurements. The current supply to the receiver was obtained from a low-frequency valve

oscillator, coupled to the receiver through a valve amplifier so that its frequency calibration should not be upset by a varying load. The voltage across the receiver was measured by means of a calibrated rectifying valve and kept constant by means of a rheostat in series with the receiver. The current through the receiver was measured by a hot-wire milliammeter (Duddell) and a few points were obtained with the receiver diaphragm damped with the finger. The readings are given in cols. 1, 2 and 3 of Table 1 and

TABLE 1.

(*Voltage across Receiver* = 2·2 *Volts.*)

1	2	3	4	5	6
f	i	i_d	$Z=\frac{2\,200}{i}$	$Z_d=\frac{2\,200}{i_d}$	$Z'=\frac{Z}{Z_d}$
p.p.s.	mA	mA	ohms	ohms	
651	8·10	8·65	272	254	1·070
704	7·30		301	263	1·145
711	7·60		290	264	1·100
716	8·21	8·3	268	265	1·010
723	9·02		244	266	0·917
739	10·40		212	269	0·790
753	10·3		214	272	0·788
775	9·5	8·0	232	275	0·850

are plotted as the i curve and the i_d curve in Fig. 5. The value of Z is entered in col. 4, and that of Z_d derived from the i_d curve in col. 5. In col. 6 is entered the value of the ratio $Z' = Z/Z_d$, and this is plotted against the frequency in Fig. 6. In this figure the construction described above is carried out to obtain the circle, and from this circle the resonant frequency and the decay factor can be obtained.

In order to see how far this circle does actually represent the conditions as the frequency changes, a connection must be found between the frequency and the position of the corresponding vector. It is known [see Equation (1)] that the angle of the mechanical impedance of the diaphragm α is given by

$$\tan\alpha = \frac{m\omega - (s/\omega)}{r}$$

whence $$\omega^2 - \frac{r}{m}\tan\alpha\omega - \frac{s}{m} = 0$$

and $$\omega = \frac{r}{2m}\tan\alpha \pm \sqrt{\left(\frac{r^2}{4m^2}\tan^2\alpha + \frac{s}{m}\right)}$$

For values of α up to, say, 75°, $r^2/(4m^2)\tan^2\alpha$ is much smaller than s/m in the telephone receiver case and may be neglected. Further, $\Delta = r/2m$ and we may write

$$\omega = \sqrt{\frac{s}{m}} + \Delta\tan\alpha$$

That is to say, the relation between ω and $\tan\alpha$ should be a straight line, the intercept of which on the ω axis ($\tan\alpha = 0$) gives the value ω_0 corresponding to the resonant frequency, and the slope of which is equal to Δ. If f is plotted instead of ω, the intercept is f_0 and the slope $\Delta/2\pi$.

Points on this line are found from Fig. 6 and from

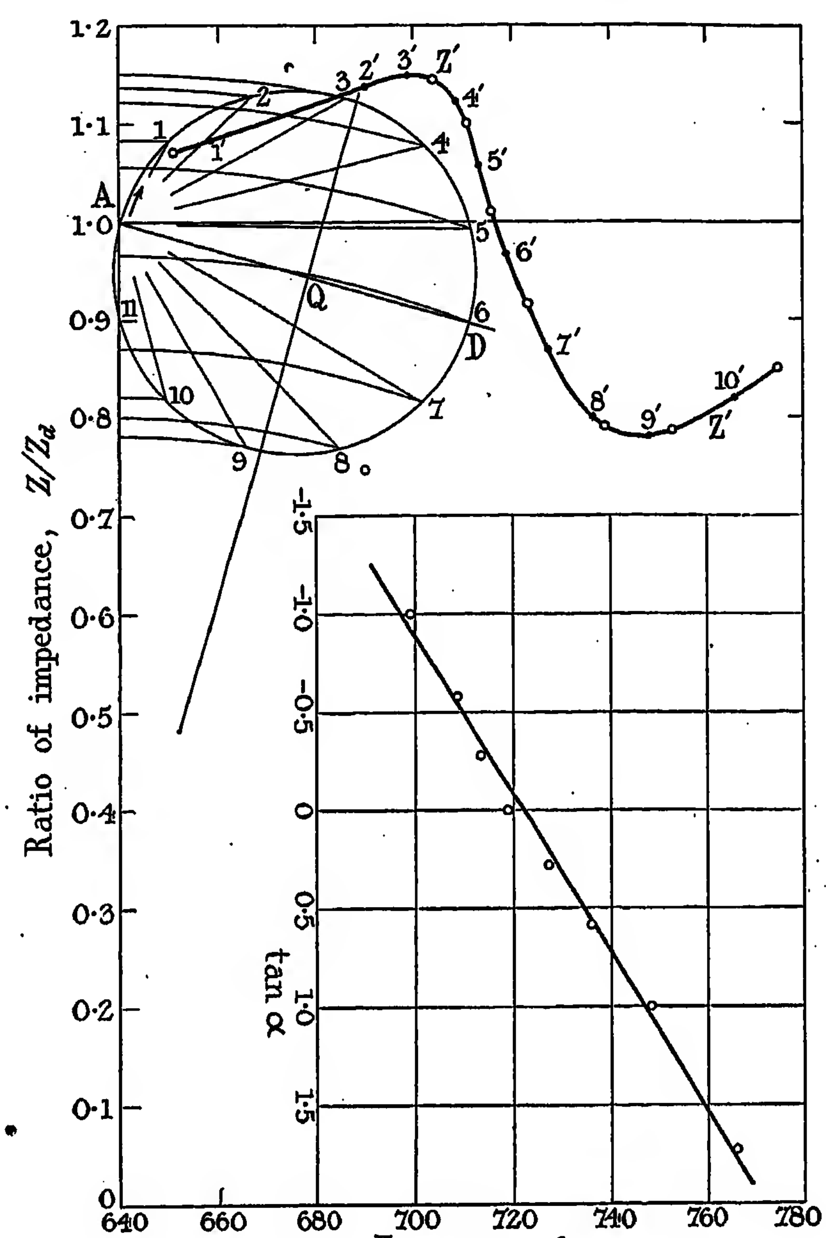


FIG. 6.

Table 2 as follows. Lines are drawn from A making angles with AD of 75°, 60°, 45°, 30° and 15° on each

TABLE 2.

1	2	3	4
Reference no.	α	$\tan\alpha$	f
	degrees		p.p.s.
1	− 75	− 3·73	659
2	− 60	− 1·73	690
3	− 45	− 1·00	699
4	− 30	− 0·577	708
5	− 15	− 0·268	714
6	0	0	719
7	15	0·268	727
8	30	0·577	736
9	45	1·00	748
10	60	1·73	766

side and cutting the circle in the points 1, 2, 3, . . . 10. These points are the reference numbers of col. 1 in Table 2, col. 2 gives the angle α, and col. 3 its tangent. The frequencies are ascertained by finding the corresponding points on the resonance curve, i.e. by drawing arcs with O1, O2, etc., as radii and O as centre to meet the axis OY in points through which horizontal lines are carried to meet the resonance curve in the points 1′, 2′, 3′, 4′ . . . 10′. The frequencies at these points are entered in col. 4. The curve between tan α and f is plotted in the lower part of Fig. 6, using a vertical scale for tan α and the original frequency scale. It is seen that the points closely approximate to a straight line from 3 to 10 inclusive, and from the line it appears that the resonant frequency is 722 and that

$$\Delta = 2\pi \times \text{slope} = 2\pi \times 25 = 157$$

5. Graphical Construction from Current Curve and Current Circle.

An examination of the results so far obtained suggests that the whole of the work may be done graphically from the current/frequency readings. For, since

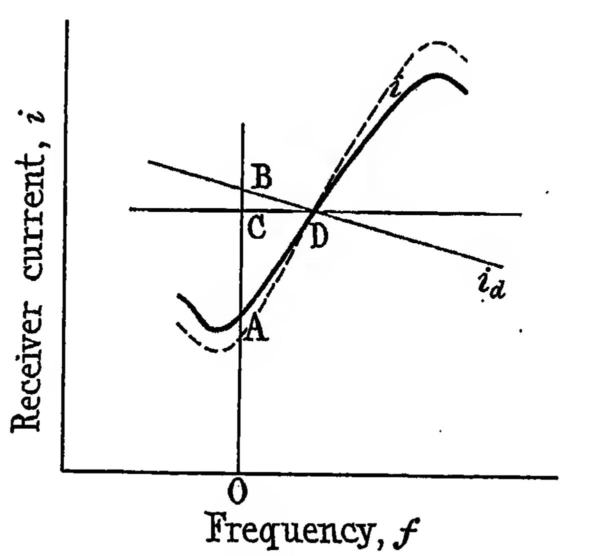


Fig. 7.

$i = e/Z = e/(Z_d\underline{|\theta} + Z_r\underline{|\chi})$ and, with diaphragm damped, $i_d = e/(Z_d\underline{|\theta})$

$$\frac{i}{i_d}\angle = \frac{Z_d\underline{|\theta}}{Z_d\underline{|\theta} + Z_r\underline{|\chi}} = \frac{1}{1 + \frac{Z_r}{Z_d}\underline{|\chi - \theta}} = i'\angle$$

Since $1 + \frac{Z_r}{Z_d}\underline{|\chi - \theta}$ has approximately a circular locus, so also has its reciprocal $1\Big/\left(1 + \frac{Z_r}{Z_d}\underline{|\chi - \theta}\right)$. The latter circle (which will be called the current circle) can be drawn from the $(i/i_d, f)$ curve in exactly the same way as the original circle (which will now be called the impedance circle) was drawn from the $(Z/Z_d, f)$ curve, and the impedance circle (its reciprocal) obtained by the method of inversion.*

Also, since the variations of i_d over the frequency-range required are small, and the change of i is only a fraction of the total i, the division i/i_d may be carried out by a simple subtraction. Through the point D (Fig. 7) where the i_d curve cuts the i curve draw a horizontal straight line. At any ordinate OACB, OA $= i$, and OB $= i_d$,

$$\therefore \frac{i}{i_d} = \frac{\text{OA}}{\text{OB}} = \frac{\text{OA}}{\text{OC} + \text{CB}}$$
$$\doteqdot \frac{\text{OA} - \text{CB}}{\text{OC}}$$

since CB is small compared with OA and OC, and OA does not differ greatly from OC. Hence, if the scale is so chosen that the length OC is unity, the ratio i/i_d is obtained simply by subtracting the intercept CB from OA on the left-hand side of the point where the i and i_d curves cross, and adding it on the right. (Or, in other words, taking the intercept between the i and i_d curves and subtracting it from or adding it to the height of the horizontal line, as the case may be.)

This is done in Fig. 8 to obtain the points 1, 2, 3, 4, 5, 6, 7 and 8 from the original i/f and i_d/f curves. The points 1, 2, 3, etc., are obtained from the actual observation points on the i/f curve. From this curve the circle A_i 1′, 2′, 3′, . . . 8′ is drawn as before. This is the "current" circle $1\Big/\left(1 + \frac{Z_r}{Z_d}\underline{|\chi - \theta}\right)$ with scale $OA_i = 1$.

To invert this through its centre Q_i draw a straight line OQ_i cutting the circle in a_i and b_i. Scale off the lengths $Oa_i = 7{\cdot}2/8{\cdot}3$ and $Ob_i = 10{\cdot}62/8{\cdot}3$. Then marking off $Oa_z = 8{\cdot}3/7{\cdot}2 = 1{\cdot}151$ and $Ob_z = 8{\cdot}3/10{\cdot}62 = 0{\cdot}78$ along the same line OQ_i gives two points, a_z and b_z, on the inverted circle. A further point A_z will be $1/OA_i$ on the OY axis, and this length, OA_z, is unity. So make OA_z unity on any suitable scale (of course marking off Oa_z and Ob_z to the same scale), and draw the circle $a_zb_zA_z$ with centre Q_z. Then this is the impedance circle obtained before, viz. $1 + \frac{Z_r}{Z_d}\underline{|\chi - \theta}$.

To obtain points on the curve between f and tan α it is necessary to proceed from the impedance circle via the current circle to the resonance curve, or vice versa. The points 1′, 2′, 3′, . . . 8′ on the current circle corresponding to the points 1, 2, 3, . . . 8 on the resonance curve are found by drawing horizontals through the latter points to meet OY, and through the points of intersection drawing arcs with centre O to meet the circle. The corresponding points on the impedance circle are found by drawing rays O1′, O2′, O3′, . . . O8′ to meet the impedance circle in 1″, 2″, 3″, . . . 8″. A straight line is now drawn perpendicular to the diameter A_zQ_z at a distance A_zO''' equal to unity, and the rays A_z2'', A_z3'', etc., meet this line in the points 2‴, 3‴, 4‴, . . . 8‴. Then the lengths O‴2‴, O‴3‴, O‴4‴ . . . are the values of tan α corresponding to the frequencies at the original points, 1, 2, 3, etc. Points on the f/tan α curve are obtained in the lower part of the diagram by marking off the lengths O‴2‴, O‴3‴, etc., vertically, and drawing horizontals

* Miles Walker: *Electrician*, 1923, vol. 90, p. 215.

through the points obtained to intersect the verticals through the points 2, 3, 4 . . . 8. It is seen that the points so obtained lie very nearly on a straight line, and lines $f/\tan\alpha$ of Figs. 6 and 8 are identical, though in the latter case the actual observational points are used, and in the former α is taken at definite values.

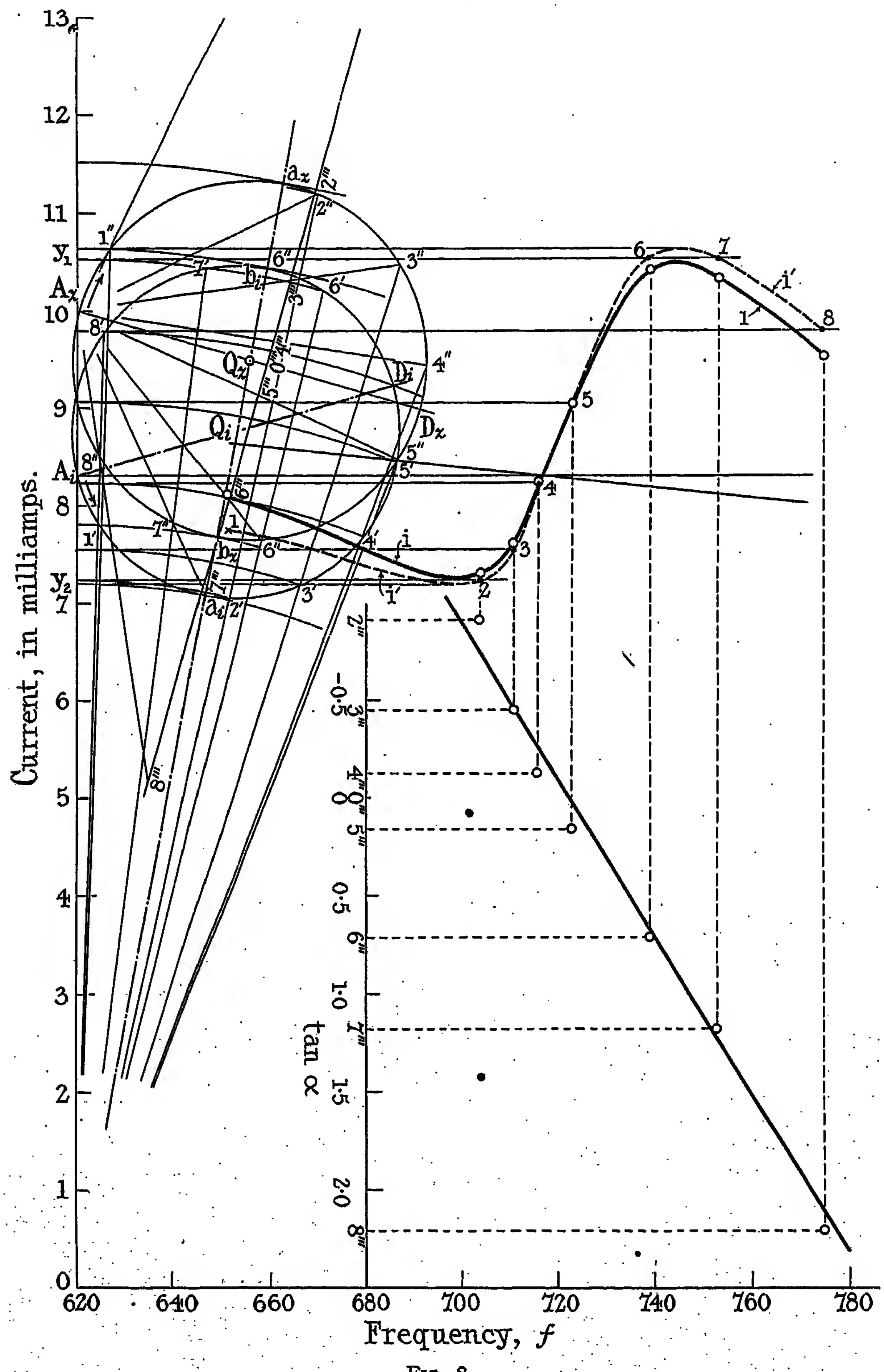


Fig. 8.

and the resonant frequency and decay factor obtained from the latter are the same as those previously obtained. In fact, the same scale having been chosen for the impedance circle as before, the impedance circle

The impedance-circle scale could of course be chosen so as to make the two circles coincide, and this would generally be done if f_0 and Δ were required for a number of curves. It is thought, however, that in

explaining the method the construction of two separate circles leads to greater clearness.

6. More Approximate Simple Methods in Special Cases.

In cases where the alteration of impedance is small compared with the whole impedance, i.e. when the point O is a considerable distance from the circle compared with its diameter, the arcs drawn with centre O to the circle are practically straight lines at right angles to the axis OY. In other words, the points on the circle corresponding to the points on the modified resonance curve (Z' or i') are obtained by direct projection from the latter at right angles to OY to meet the circle. Further, instead of drawing the modified resonance curve the circle may be tilted round by drawing it between the lines MM, mm, parallel to the Z_d line and tangential to the resonance curve as indicated in Fig. 9.* The point A where the line Z_d meets the circle corresponds to the previous point A, AD is the diameter, and a line through D parallel to MM to meet the circle in r determines the resonant frequency f_0. Obviously in this case f_0 can be found without drawing the circle, by drawing a line RR parallel to Z_d and at the same distance from mm that Z_d is from MM, to meet the curve in r. Also, having drawn the circle, Δ can be found from the quadrantal points simply by drawing a diameter at right angles to AD meeting the circle in T and S, and through T and S drawing parallels to MM to meet the resonance curve in the corresponding points t and s, at frequencies f_1 and f_2. Then $\Delta = \pi(f_2 - f_1)$. Or the construction described above may be used to obtain the line $f/\tan\alpha$, all projections from the curve to the circle being made parallel to mm.

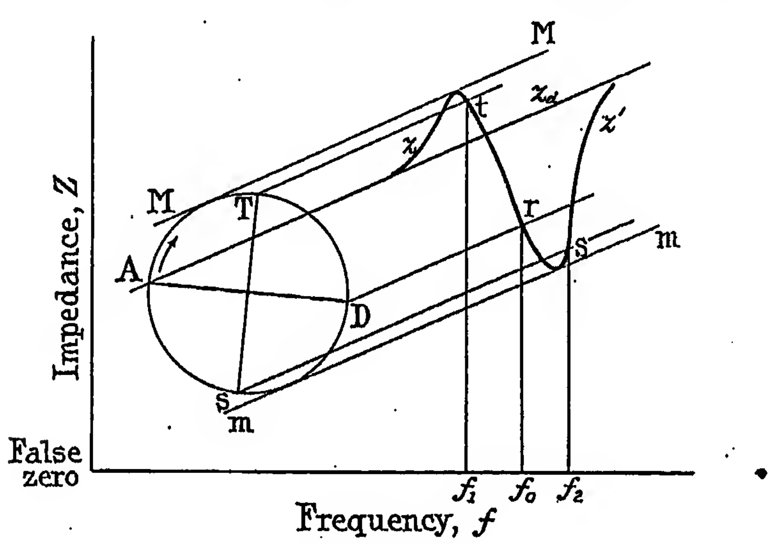


Fig. 9.

Working from the current curve instead of the impedance curve, the construction is precisely the same. Taking for simplicity the modified resonance (current) curve, the current circle is drawn between the horizontal lines MM and mm. The scale of the impedance circle is so chosen that the two circles coincide (though they are shown separately in Fig. 10 for clearness). Since the origin O is assumed to be at a great distance the invertion from one circle to the other is carried out by drawing lines parallel to OY, as approximately the same thing as drawing rays from O. Thus the diameter A_zD_z, which determines the resonance frequency, corresponds nearly to the diameter A_iD_i, and the quadrantal points S_z and T_z to the points S_i and T_i which are also quadrantal. The construction described in the previous paragraph can therefore be used on either the impedance or the current curve, though the accuracy will be rather greater in the former case.

Even in the experimental case given, where the resonance impedance range is about one-third of the whole impedance, this simple method for the resonance frequency leads to good results. Carried out on the impedance curve of Fig. 5, a value of f_0 of 722 is found, and on the current curve, 726. For Δ, from the impedance circle as drawn the quadrantal frequencies are 703 and 750, giving $\Delta = \pi(750 - 703) = 148$. In the case of the current circle they are 707 and 754, leading to the same result. So that the agreement with

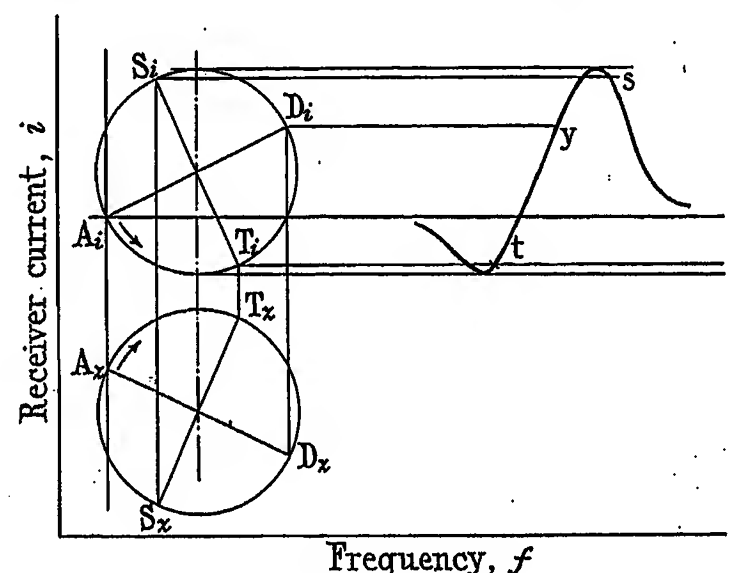


Fig. 10.

the value obtained by the more accurate method is not so good as in the case of f_0.

In the case of the higher modes of vibration of a receiver diaphragm, where the effect of the resonance on the impedance is not nearly so marked, the simpler method will be quite satisfactory. Curves obtained in two cases, those of two nodal diameters and one nodal circle, are reproduced in Fig. 11 and it is found that in the former case $f_0 = 2\,240$ and $\Delta = 116$, and in the latter $f_0 = 2\,990$ and $\Delta = 138$.

7. Other Applications.

The methods developed have applications in other directions apart from the telephone receiver. For instance, the simple resonance curve drawn from the relation $i = \dfrac{e}{R + j[\omega L - (1/\omega C)]}$ (Fig. 12) is a special case in which the circle is drawn with the diameter AD vertical and the point A at O, and the diameter is equal to the height of the resonance. Drawing the diameter ST to obtain the quadrantal points, and arcs TT′, SS′ with centre A and radius AT to meet AD in T′ and S′ (coinciding), the points s and t on the

* This involves a reduction in the size of the circle in the ratio of 1 to cos γ (γ is the angle the line makes with the horizontal). Z' is measured as the perpendicular distance from a new OX axis parallel to Z_d and cutting the original axis at the point where it is met by the line at right angles to Z_d through K.

resonance curve are obtained by projection. This construction is obviously in agreement with the well-known rule of drawing the line st at a height $= i_{max.}/\sqrt{2}$. But instead of depending on these two points alone the construction described for finding the line $f/\tan\alpha$

The value of Δ derived from the line $f/\tan\alpha$ is $16\cdot14$ and that calculated from $\Delta = R/2L = 16\cdot10$, in close agreement.

Another electrical case which is very similar to that of the telephone receiver is the one indicated in Fig. 13.

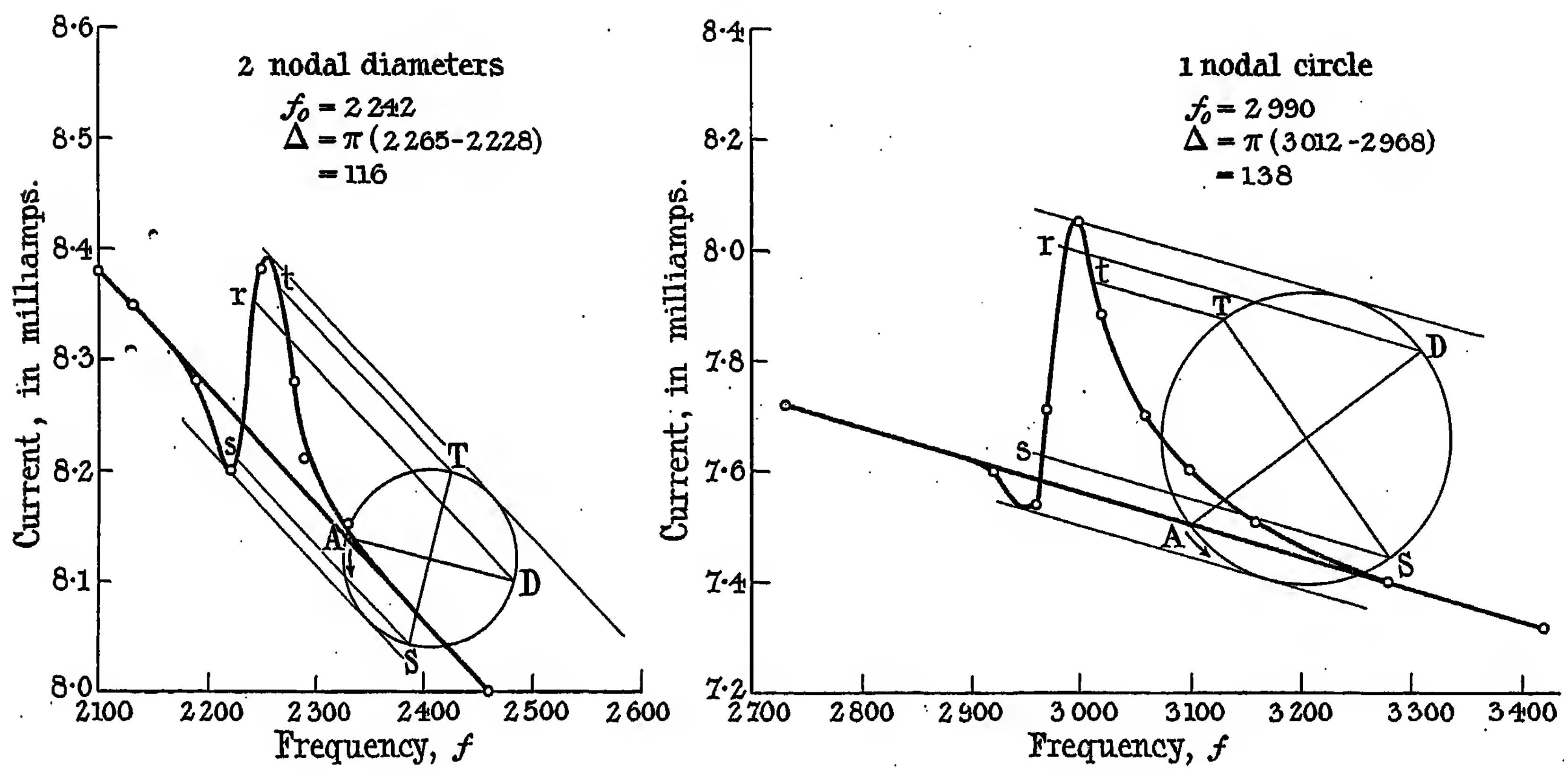


FIG. 11.

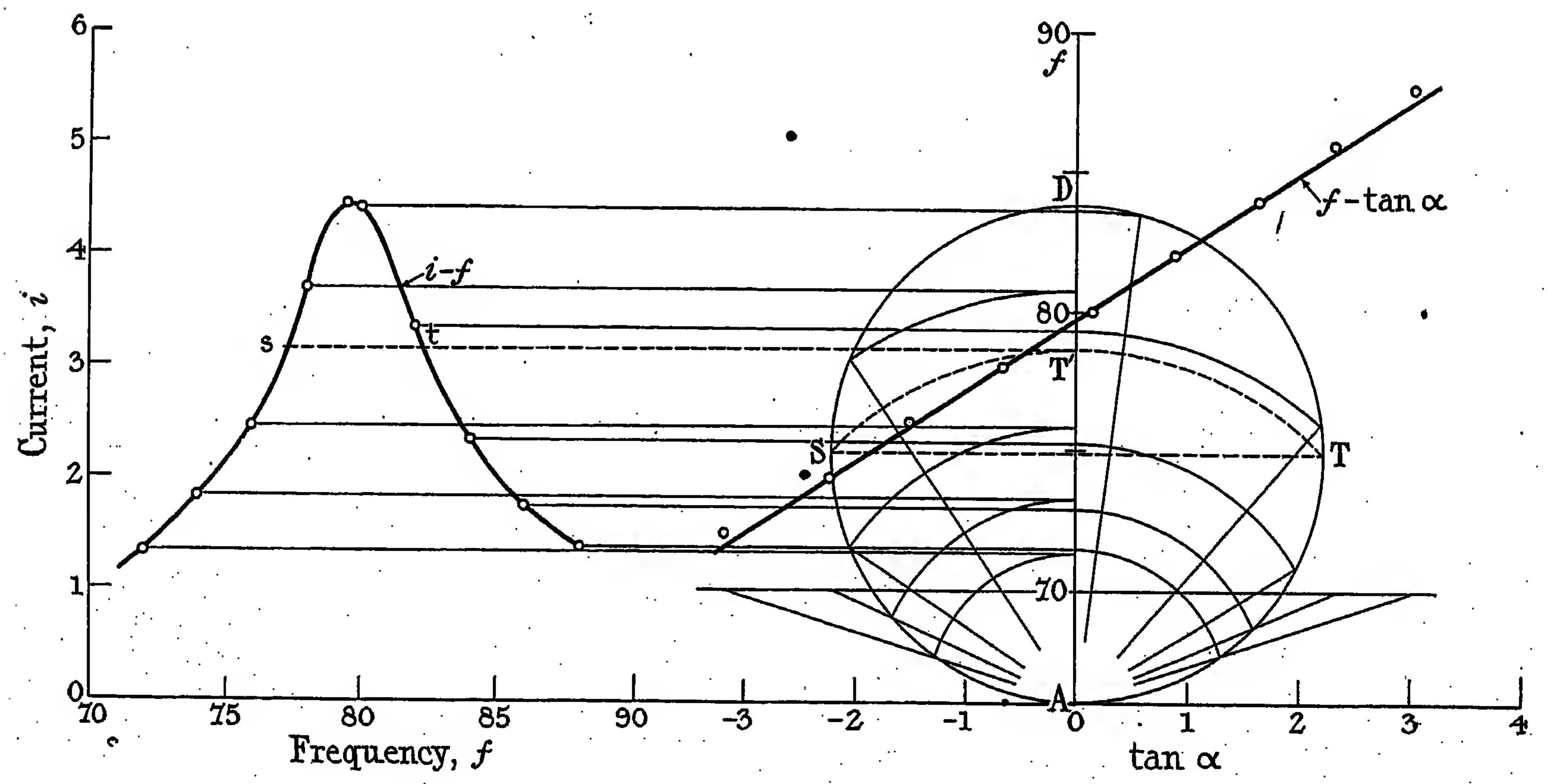


FIG. 12.

is carried out and Δ obtained from its slope. This leads to more accurate results, and at the same time is a check on the accuracy of the readings from which the resonance curve is drawn. In the case illustrated $R = 4\cdot5$ ohms, $C = 28\cdot6\mu$F and $L = 0\cdot14$ H.

The currents i_1, i_2 in the two circuits are obtained from the equations

$$v = Z_1 i_1 + j\omega M i_2$$

and

$$0 = Z_2 i_2 + j\omega M i_1$$

Eliminating i_2 we get

$$v = Z_1 i_1 + \frac{\omega^2 M^2}{Z_2} i_1$$

or

$$i_1 = \frac{v}{Z_1 + (\omega^2 M^2 / Z_2)}$$

TABLE 3.

1	2	3	4
f	i_1	i_d	$Z' = \frac{i_d}{i_1}$
p.p.s.	mA	mA	
60	0·73	1·26	1·73
62	0·63	1·20	1·90
64	0·52	1·16	2·23
66	0·60	1·12	1·87
70	1·80	1·06	0·59
71·8	2·20	1·03	0·47
74	2·20	1·00	0·45
78	1·80	0·97	0·54

being sufficiently constant over a frequency-range near resonance for the locus of Z' to be very nearly circular.

The construction has been applied to some experimental results for a circuit of this type given by

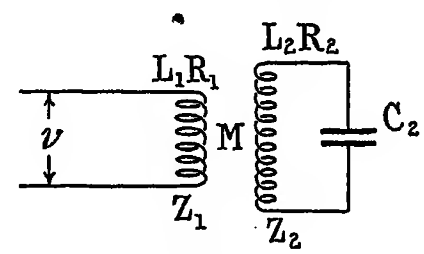


FIG. 13.

Morecroft.* The constants of the secondary circuit are $L_2 = 0{\cdot}206$ H, $C_2 = 28{\cdot}6\ \mu$F, $R_2 = 7{\cdot}2$ ohms. whence

$$f_0 = \frac{1}{2\pi}\sqrt{\left(\frac{1}{C_2 L_2}\right)} = 65{\cdot}8 \quad \text{and} \quad \Delta = \frac{R_2}{2L_2} = 17{\cdot}5$$

Cols. 1, 2 and 3 of Table 3 give the experimental values of the frequency and the corresponding current in the primary circuit first with the secondary circuit in position and secondly with it removed. Col. 4 gives the calculated value of $Z' = i_d/i_1$ and this is plotted

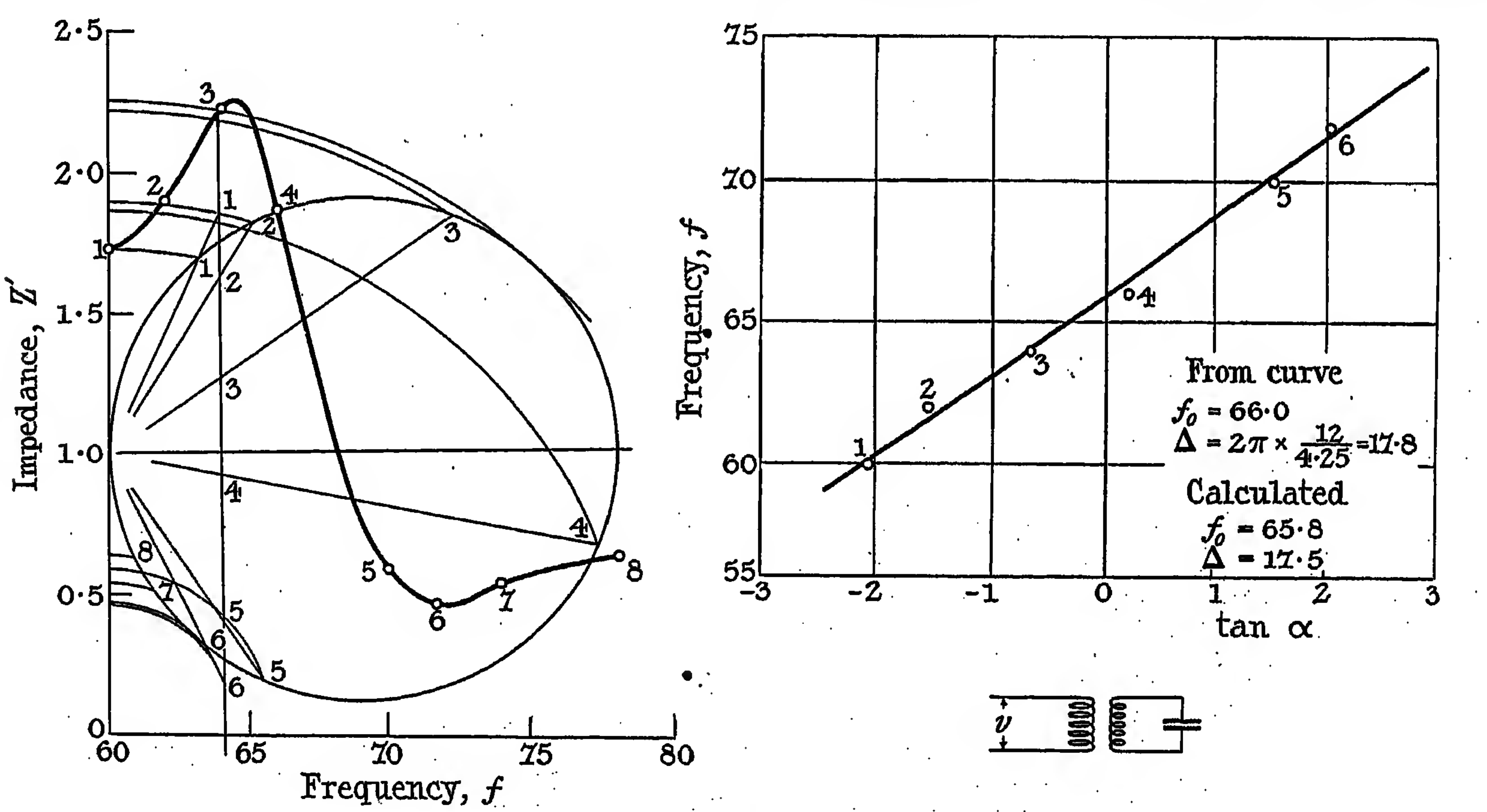


FIG. 14.

If the secondary circuit is removed we have $i_d = v/Z_1$, so that

$$Z' = \frac{Z}{Z_d} = \frac{i_d}{i_1}$$

$$= 1 + \frac{\omega^2 M^2}{Z_1} \times \frac{1}{Z_2}$$

This is of similar form to the telephone receiver Equation (2), and, provided that the resonance is fairly sharp (which will be the case in most telephone and high-frequency circuits), $\omega^2 M^2 / Z_1$ can be regarded as against frequency in Fig. 14. Here the construction as previously described is carried out for the impedance circle and the line $f/\tan\alpha$, and from the latter are obtained the values $f_0 = 66{\cdot}0$ and $\Delta = 17{\cdot}8$, in good agreement with the calculated values.

The method can be applied to the measurement of high-frequency resonances and resistances, of circuits or of coils alone. A great advantage is that a knowledge of the primary impedance and of the coupling is unnecessary. Experiments are being made to ascertain its value in this direction.

* "Principles of Radio Communication," p. 92.

REPORT OF THE COUNCIL FOR THE YEAR 1923–1924 PRESENTED AT THE ANNUAL GENERAL MEETING OF 8 MAY, 1924.

CONTENTS.

REPORT.

The Council, at the Fifty-second Annual General Meeting of the Institution of Electrical Engineers, present to the members their Report for the year 1923–24, covering approximately the period from the 1st April, 1923, to the 31st March, 1924.

The continued progress and prosperity of the Institution during the period under review afford much satisfaction to the Council.

(1) "Chartered Electrical Engineer."

A new Bye-Law sanctioning and regulating the use of the designation "Chartered Electrical Engineer" by Members and Associate Members of the Institution, which was passed at a Special General Meeting of Corporate Members held on the 28th February, 1924, was allowed at a Meeting of His Majesty's Privy Council held at the Council Chamber, Whitehall, London, on the 20th March, 1924, and came into operation on the latter date.

The privilege is one which attaches to Members and Associate Members as individuals. The Council feel confident that they will receive the support of all members in preserving the strict use of a title which confers an honourable distinction.

(2) Liquidation of the Old Institution.

The final winding-up of the old Institution, made necessary by the incorporation under Royal Charter, was effected at a Special General Meeting of Corporate Members and Associates held on the 19th July, 1923.

(3) Membership of the Institution.

The changes in the membership since the 1st April, 1923, are shown in a table given in Appendix A.

The following table shows the growth of membership for the last few years :—

Year	Membership	Increase or Decrease
1914	7 045	− 39
1915	6 811	− 234
1916	6 676	− 135
1917	6 613	− 63
1918	6 667	+ 54
1919	7 023	+ 356
1920	8 146	+ 1 123
1921	9 449	+ 1 303
1922	10 275	+ 826
1923	10 911	+ 636
1924	11 415	+ 504

It will be seen from the above that the rate of increase of the membership of the Institution is well maintained.

The largest increase has taken place in the class of Students, of whom a large number are following courses of instruction leading to certificates and diplomas, the possession of which will entitle the holders to exemption from the Associate Membership Examination.

(4) Annual Subscriptions.

At the last Annual General Meeting, the then President announced that the Council had decided, under the powers conferred upon them by Bye-Law 27, to reduce the annual subscriptions of Corporate Members by ten shillings and those of Graduates by five shillings from the 1st January, 1924.

(5) Examinations.

The Associate Membership Examination was held in April and October 1923 in London, Chatham, Birmingham, Manchester, Newcastle-on-Tyne, Cardiff, and Glasgow, and also in New Zealand and South Africa. The candidates examined included a number of officers of the Corps of Royal Engineers, who sat for the examination for the purpose of qualifying for "Engineer Pay."

For the purpose of qualifying for "Signal Pay," officers of the Royal Corps of Signals were also examined by the Institution in the "Theory of Electrical Military Signalling" at the Signal Service Training Centre, Maresfield Park Camp, Sussex, in August 1923 and February 1924.

A certain number of candidates submitted theses and papers during the year in lieu of the examination.

(6) Honorary Members.

The Council have pleasure in recording that, as announced at the Ordinary Meeting of the 1st November, 1923, they have elected Colonel Rookes Evelyn Bell Crompton, C.B., to be an Honorary Member of the Institution. Colonel Crompton became a member of the Institution in 1880 and was President in 1895 and 1908.

There are now ten Honorary Members.

(7) Honours and Distinctions Conferred on Members.

Since the last Annual Report the following honours have been conferred on members :—

Knighthood.
Barker, R. C., C.I.E. (Member).
Hume, G. H. (Member).

C.B.
McClelland, W., O.B.E. (Member).

C.M.G.
Butters, J. H., M.B.E. (Member).

O.B.E.
Fuller, Major A. C., R.C.S. (Associate Member).

M.B.E.
Butters, J. H. (Member).

The President of the Institution has been nominated for election as a Fellow of the Royal Society.

(8) Faraday Medal.

The third award of the Faraday Medal has been made by the Council to Dr. S. Z. de Ferranti, Past-President.

(9) War Memorial.

The War Memorial Book containing the biographical notices and portraits of the members of the Institution who fell in the war of 1914–1918 is in the press and will be published shortly.

(10) Deaths.

The Council regret to have to record the deaths of the following 55 members of the Institution during the year :—

Honorary Member.

Leblanc, Maurice.

Members.

Ayrton, H. (Mrs.).	Mitchell, H. E.
Chew, W.	Rawson, F. L.
Clarke, E. F.	Smith, D. C.
Dearlove, A. L.	Steinmetz, Prof. C. P.
Dixon, R. E.	Thomson, H. Lyon.
Gott, A. E.	Thorp, E. L.
Grant, A. E.	Tobler, Prof. Dr. A.
Head, H. C.	Turnbull, R. T.
Heaviside, A. W., I.S.O.	Ullett, J. W.
Kidd, G. W.	Wilkinson, H. T.
Layton, G.	Yale, T. P. O.

Associate Members.

Andrews, J. L.	Kerr, J. A. W.
Ascoli, G. H. D., M.C.	Kirloskar, V. G.
Bishop, O. H.	McIntosh, A.
Cawood, S. D.	Mallalieu, V.
Day, F.	Martin, C.
Garstang, F. L.	Owen, C. M.
Handley, G. W.	Pauls, S.
Hement, T. C.	Rowell, W. N.
Hounsfield, F. C.	Swire, S.
Hughes, A. S.	Wallwork, T.

Williamson, A.

Graduate.

Slater, J. T. L.

Students.

Imeary, R. K. — MacKenzie, K. S.

Nicholas, J. D.

Associates.

Benest, H.	Dennison, J. D.
Clapperton, G.	Donnison, F. A.
Crawford, F. C.	Mostyn, R. J. F.

Nicholl, H.

The Council particularly deplore the loss to Electrical Engineering caused by the deaths of Monsieur Maurice Leblanc (elected Hon. Member, 1915), Mrs. H. Ayrton (elected Member, 1899), Mr. A. W. Heaviside, I.S.O. (Chairman of the Newcastle Local Section, 1900–1; awarded Fahie Premium, 1892), and Prof. C. P. Steinmetz (elected Member, 1912).

(11) Institution Building.

A very large number of meetings of kindred societies have been held in the Institution building during the past twelve months and it has been a pleasure to the Council to have been able to grant the use of the premises for this purpose. In particular, mention

should be made of the Jubilee Celebrations of the Physical Society of London, which were held on the 20th, 21st and 22nd March, 1924.

(12) MEETINGS.

Four hundred and eight meetings have been held during the past twelve months and a complete statement is contained in Appendix B.

(13) PREMIUMS.

The following Premiums for papers have been awarded by the Council :—

The Institution Premium (*value* £25).

Lt.-Col. H. E. O'BRIEN, D.S.O.	"The Future of Main-Line Electrification on British Railways."

The Ayrton Premium (*value* £10).

A. BACHELLERY.	"Electrification of the French Midi Railway."

The Fahie Premium (*value* £10).

P. E. ERIKSON and R. A. MACK.	"Transmission Maintenance of Telephone Systems."

The John Hopkinson Premium (*value* £10).

A. S. FITZGERALD.	"The Design of Apparatus for the Protection of Alternating-Current Circuits."

The Kelvin Premium (*value* £10).

H. M. BARLOW, B.Sc. (Eng.), Ph.D.	"An Investigation of the Friction between Sliding Surfaces."

The Paris Premium (*value* £10).

H. MARRYAT.	"Electric Passenger Lifts."

The Webber Premium (*value* £10).

S. C. BARTHOLOMEW.	"Power Circuit Interference with Telegraphs and Telephones."

A Premium (*value* £10).

E. A. WATSON, O.B.E.	"Permanent Magnets, and the Relation of their Properties to the Constitution of Magnet Steels."

A Premium (*value* £5).

E. A. CLAYTON, D.Sc. (Eng.).	"A Mathematical Development of the Theory of the M.M.F. of Windings."

A Premium (*value* £5).

Prof. W. CRAMP, D.Sc., and Miss N. I. CALDERWOOD, M.A., B.Sc.	"The Calculation of Air-space Flux."

A Premium (*value* £5).

F. J. TEAGO, M.Sc.	"The Nature of the Magnetic Field produced by the Stator of a Three-phase Induction Motor."

WIRELESS SECTION PREMIUMS.

A Premium (*value* £10).

L. B. TURNER, M.A.	"The Relations between Damping and Speed in Wireless Reception."

A Premium (*value* £10).

R. H. BARFIELD, M.Sc.	"Some Experiments on the Screening of Radio Receiving Apparatus."

A Premium (*value* £5).

C. E. HORTON.	"Wireless Direction-Finding in Steel Ships."

A Premium (*value* £5).

E. B. MOULLIN, M.A.	"Atmospherics, and their Effects on Wireless Receivers."

The award of Premiums for papers read before the Students' Sections will be announced later.

(14) ORDINARY MEETINGS.

Before the commencement of the Session a circular was sent to members in the London area with the object of ascertaining the most convenient hour for the Ordinary Meetings. The replies received showed a large majority in favour of 6 p.m. and the Council accordingly decided to continue holding the meetings at that hour.

(15) LOCAL CENTRES AND SUB-CENTRES.

The attendances at meetings of the Centres and Sub-Centres have been satisfactorily large and the interest in the discussions has been generally well sustained.

The President has attended functions or meetings at the Centres at Birmingham, Cardiff, Dublin, Glasgow, Leeds, Liverpool, Manchester and Newcastle, and the Sub-Centre at Sheffield, and on each occasion he has addressed the members.

(16) LOCAL CENTRE ABROAD.

The Council have sanctioned the formation of a Local Centre of the Institution in China, with headquarters at Shanghai.

(17) WIRELESS SECTION.

The Council are gratified at the continued success of the Wireless Section. Nine meetings have been held, at which 10 papers were read.

(18) INFORMAL MEETINGS.

During the Session 13 meetings were held, being two more than last session. The average attendance per meeting has materially increased.

That the subjects discussed have met with approval has been shown by the keenness of the debates, and there is no doubt that the Informal Meetings are serving a very useful purpose.

(19) STUDENTS' SECTIONS.

A very full programme of meetings, visits to works, and social functions was carried out during the Session by the eight Students' Sections now in existence,

viz. in London, Birmingham, Glasgow, Leeds, Liverpool, Manchester, Newcastle and Sheffield.

Addresses to the London Students' Section were given by the President and Mr. C. F. Elwell, Member.

A Students' visit to Belgium and Holland took place from July 24th to August 4th, 1923. The following works, etc., were visited: at Antwerp, Minerva Motors & Bell Telephone Manufacturing Co.; at Liége, Messrs. Cockerill's Steel Works, Les Cristalleries du Val St. Lambert, and the University; at Kostwijk (Holland), the Radio Station. The party also called at Brussels, Eindhoven, Apeldoorn, Amsterdam and The Hague. At Liége the British Consul arranged for members of the party to become Honorary Members of the Anglo-Belgian Club. The tour was extremely successful, 40 Students taking part in it.

The firms named have been thanked for the courtesy shown by them on the occasion and for the facilities afforded, which very materially helped to make the visit an acknowledged success.

The Council have to thank Mr. A. C. Warren (Assistant Honorary Secretary, London Students' Section) for his valuable work in organizing the visit.

(20) Scholarships.

The following Scholarships have been awarded by the Council:—

David Hughes Scholarships.

(Value £50 each; tenable for one year.)

R. E. Banks (Birmingham University).
R. MacWhirter (Royal Technical College, Glasgow).

Salomons Scholarships.

(Value £50 each; tenable for one year.)

F. J. Lane (Leeds University).
J. Linton (Heriot Watt College, Edinburgh).

War Thanksgiving Education & Research Fund (No. 1).

A grant of £100 for educational purposes has been made this year by the Council under the provisions of the Trust Deed to A. Ramsay (Glasgow University).

(21) Coopers Hill War Memorial Prize.

The award of the Coopers Hill War Memorial Prize, which consists of a Bronze Medal, a parchment Certificate of Award and a Money Prize of £29, fell this year to the Institution and the Council selected for the award Mr. F. R. Combes for his monograph entitled "An Historical and Critical Survey of Atmospheric Electricity and Protection against Lightning."

It may here be recalled that the Prize was founded by members of the Royal Indian Engineering College, Coopers Hill, in commemoration of members of the College who fell during the late war. It consists of two awards, one of which is made annually by the Institution of Civil Engineers and the other triennially in turn by the Institution of Electrical Engineers, the School of Military Engineering, Chatham, and the School of Forestry, Oxford, for the best paper on a professional subject selected by the Council making the particular award.

(22) Conversazione.

The Annual Conversazione was held at the Natural History Museum, South Kensington, London, on the 28th June, 1923, when over 1 500 members and guests attended.

(23) Annual Dinner.

The Annual Dinner was held at the Hotel Cecil, London, on the 21st February, 1924, the members and guests present numbering 487.

An account will be found in the *Journal*, vol. 62, p. 350.

(24) Summer Meeting.

A most successful Summer Meeting, attended by some 450 members and ladies, was held from the 5th to the 8th June, 1923, at the Manchester and Liverpool Centres, two days being spent in Manchester, one in Liverpool and one in North Wales. A full and interesting programme of functions, excursions and visits to works was arranged by the Committees of the two Centres. During the Meeting the works, etc., of the following were visited:—

Messrs. R. Johnson & Nephew, Ltd., Bradford.
Messrs. Mather & Platt, Ltd., Manchester.
The No. 2 Dunlop Rubber Cotton Mills, Ltd., Rochdale.
Messrs. Pilkington's Tile and Pottery Works, Clifton Junction.
The Chloride Electrical Storage Co., Ltd., Clifton Junction.
The London, Midland & Scottish Railway Company's Power Stations at Clifton Junction and at Formby.
The Lancashire Electric Power Company's Station, Ratcliff.
The Manchester Corporation's new Generating Station at Barton, and their 33 000-volt Substation at Chorlton-on-Medlock.
The Metropolitan-Vickers Electrical Co., Ltd., Trafford Park.
The Lancashire Dynamo and Motor Co., Ltd., Trafford Park.
The *Manchester Guardian* Offices, Manchester.
The British Insulated & Helsby Cable Co., Ltd., Prescot.
The Liverpool Corporation's Lambeth-road Tramways Works, Automatic Substation, Walton, and the Lister-drive Power Station.
Messrs. Lever Brothers, Ltd., Port Sunlight.
The Automatic Telephone Manufacturing Co., Ltd., Liverpool.
The Mersey Power Co., Runcorn.
The United Alkali Co., Widnes.
The Aluminium Corporation, Ltd., Dolgarrog.
The North Wales Power Co.'s Hydro-Electric Power Station, Cwm Dyli.
Lord Penrhyn's Slate Quarries, Bethesda.

The party also visited the Laboratories of the University of Manchester, the Applied Electricity Laboratories of the University of Liverpool and the Cunard Steamship Company's s.s. "Scythia."

The thanks of the Institution have been conveyed to the foregoing, and also to the Lord Mayor and Lady Mayoress of Manchester, the Electricity and Tramways Committee of the Manchester Corporation, the Manchester Ship Canal Company, Sir H. A. Miers (Vice-Chancellor of the University of Manchester), the Lord Mayor and Lady Mayoress of Liverpool, the Tramways and Electric Power and Lighting Committee of the Liverpool Corporation and the London Midland & Scottish Railway Co., Ltd., who all extended most generous hospitality to the visitors.

The Council desire to put on record their appreciation of the work of the Committees of the two Centres and especially of the respective Chairmen (Mr. A. S. Barnard, Manchester, and Mr. B. Welbourn, Liverpool) and Honorary Secretaries (Mr. A. B. Mallinson, Manchester, and Mr. G. C. Waygood, Liverpool).

(25) Portraits of Past-Presidents.

The set of enlarged photographs of Past-Presidents has been completed and has for some months been hung in the Common Room.

(26) American Institute of Electrical Engineers.

At the Annual Convention of the American Institute of Electrical Engineers held at Swampscott, Mass., U.S.A., from the 25th to the 29th June, 1923, the Institution was represented by two of its Honorary Members as delegates, namely, Professor A. E. Kennelly and Professor Elihu Thomson.

(27) Société des Ingénieurs Civils de France.

Mr. R. T. Smith and Mr. C. H. Wordingham, C.B.E., Past-Presidents, represented the Institution at the meetings held in Paris on the 4th, 5th and 6th May, 1923, to celebrate the 75th Anniversary of the foundation of the Société des Ingénieurs Civils de France.

(28) Library.

During the year, 268 books and pamphlets have been presented to the Reference Library by members and others and 140 volumes have been purchased. An increase in attendance is recorded, the total number for the year being 2 590, of whom 178 were non-members, as against the previous highest yearly total of 2 526 in 1922-23.

The Council have pleasure in recording the continued circulation of books from the Lending Library. During the year 2 232 were issued to 897 borrowers, the corresponding numbers for the previous year being 2 213 and 814 respectively.

The Silvanus Thompson Memorial Library was formally presented to the Institution at the Annual General Meeting held on the 31st May, 1923. On the same occasion Mrs. Thompson presented to the Institution an oil painting of the late Dr. Thompson, and the Finsbury Old Students' Association a bronze bust of him.

The Institution is now the possessor of a painting of Sir Francis Ronalds at work on a catalogue of his Library, of which the Institution has the custody and use. The painting was presented by Mrs. Ortmans, a great-niece of Sir Francis.

(29) Electrical Appointments Board.

The number of applicants for posts registered on the 31st March, 1924, was 114 as against a total of 120 last year.

A classified Register of members seeking positions, containing particulars of their training and experience, is available for inspection at the Institution offices, and the Secretary of the Board will gladly put employers in touch with highly qualified electrical engineers.

The Council earnestly hope that members who are in a position to assist will not fail to make use of the Register.

(30) The Journal of the Institution.

The amount of matter published in the *Journal* continues to increase, the number of pages in the 1923 volume being 1 204 as compared with 1 002 in the previous volume. This increase is largely accounted for by the publication of a number of reports of the Electrical Research Association, in particular several dealing with overhead lines.

The net cost of printing and posting the *Journal* in 1923, after allowing for sales and the revenue received from advertisements, was £4 159, as compared with £4 604 in 1922 (1 002 pages) and £4 936 in 1921 (852 pages). As the number of copies printed increased from 10 200 in 1921 to 11 400 in 1923, the reduction in the net cost is most gratifying. The net cost per page works out at £5·79 for 1921, £4·59 for 1922 and £3·45 for 1923.

A Ten-Year Index to the *Journal* for the years 1912-21 was issued during the year.

(31) "Science Abstracts."

The Physics volume of *Science Abstracts* for 1923 contained 184 pages more than that for 1922; the Electrical Engineering volume contained 2 pages less. During the year the Committee of Management of the publication took steps to increase the revenue, with the result that the financial position is now satisfactory, and *Science Abstracts* does not appear in the accounts, as in the past, as a financial burden on the Institution.

(32) Wiring Rules.

The revision of the Wiring Rules has been completed, and the Council are gratified to be able to report that the Fire Offices have accepted the revised Rules, which will in future be known as "Regulations for the Electrical Equipment of Buildings." It is hoped to publish the Regulations before the end of June.

(33) Model Conditions of Contract.

The Council have approved and published Model Conditions of Contract for:—

(*a*) The sale of goods other than cables at home when no erection is included in the contract;

(*b*) The sale of cables at home when no erection is included in the contract.

Conditions of Contract for Export Orders are still

under consideration by a Committee appointed for the purpose.

(34) Electricity Regulations.

The draft Regulations for Low and Medium Pressure and for High Pressure Overhead Lines, prepared by the Electricity (Supply) Regulations Committee and submitted to the Electricity Commissioners were, with few alterations, approved by the Commissioners, and were published by His Majesty's Stationery Office in November 1923.

For the purpose of enabling the Council to submit a Report thereon to the Electricity Commissioners, the Committee are now engaged in the consideration of the Commissioners' Regulations (A) for securing the Safety of the Public, and (B) for ensuring a proper and sufficient supply of Electrical Energy.

(35) Committee on Electricity in Agriculture.

The Committee appointed last session are collecting information for their report to the Council.

(36) National Certificates and Diplomas in Electrical Engineering.

The joint Standing Committee representing the Board of Education and the Institution have approved for this Session 50 schools and colleges in England and Wales at which courses may be taken by students with a view to their being awarded National Certificates or Diplomas in Electrical Engineering. The names of the schools and colleges approved, together with the grade of Certificate or Diploma obtainable, have been published from time to time in the *Journal*. About 450 candidates will sit for the final examinations on this occasion.

(37) Engineering Joint Council.

The provisional constitution of the Engineering Joint Council which was set out in the last Annual Report has been finally approved and will be found in Appendix C to this Report, together with the Bye-Laws and Rules made by the Joint Council.

The Institution's representatives on the Joint Council are Mr. J. S. Highfield and Mr. Roger T. Smith, Past-Presidents.

(38) British Electrical Research Association.

The Director of the Association reports as follows:—

During the year the membership of the E.R.A. has been materially strengthened by the addition as Associate Members of representatives of suppliers and large users of electricity.

The Report on the Heating of Buried Cables has attracted world-wide attention. Progress has been made in dealing with cables for voltages above 11 000 and in further study of safe temperature limits. Work on insulating oils is being chiefly directed to a further raising of standards which is likely to be accomplished in the immediate future.

Patents have been applied for covering improvements in oil circuit-breakers calculated to increase the rupturing capacity materially without increase of size or cost. Work on overhead-line materials is being carried out with a view to further improvements in the construction of wood poles and completion of data for the calculation of wind pressures.

An extensive series of reports has now been published in the *Journal* giving instructions for the study of most of the principal insulating materials. The use of the methods advocated therein has resulted in further improvements in numerous directions.

The researches on steam turbines and steam condensers continue to yield valuable data.

The Institution has increased its annual subscription from £300 to £500, and a corresponding grant is being obtained from the Government.

Members are invited to communicate with the Director of the Association at 19 Tothill-street, Westminster, S.W. 1, on the work of the Association and all matters relating to co-operative research.

(39) British Engineering Standards Association.

A large number of British Standard Specifications dealing with electrical apparatus and machinery were published during the past year, as follows:—

B.S.S. No. 31. Steel Conduits for Electric Wiring (Revision).
B.S.S. No. 117. Drum Starters for Electric Motors.
B.S.S. No. 118. Drum Controllers for Electric Motors.
B.S.S. No. 123. Face Plate Controllers, and Resistances for Use therewith.
B.S.S. No. 124. Totally Enclosed Air-break Switches.
B.S.S. No. 126. Flame-proof Air-break Switches.
B.S.S. No. 127. Flame-proof Air-break Circuit Breakers.
B.S.S. No. 129. Contactor Controllers, and Resistances.
B.S.S. No. 130. Totally Enclosed Air-break Circuit Breakers.
B.S.S. No. 140. Liquid Starters for Electric Motors.
B.S.S. No. 141. Switch Starters (Star-delta and Series-Parallel) for Electric Motors.
B.S.S. No. 147. Multiple Switch Starters for Electric Motors.
B.S.S. No. 148. Insulating Oils for Use in Transformers, Oil Switches and Circuit Breakers.
B.S.S. No. 155. Contactor Starters for Electric Motors.
B.S.S. No. 157. Moulded Flat Top Insulating Bushes.
B.S.S. No. 158. Marking for Busbars and Connections.
B.S.S. No. 160. Slate Slabs for Electrical Purposes.
B.S.S. No. 166. List of Terms and Definitions for Radio Communication.
B.S.S. No. 167. Auto-transformer Starters (hand-operated pattern) for Electric Motors.
B.S.S. No. 173. Electric Performance of Traction Motors.

At the request of the Electrical Research Association, a Committee has recently been set up to prepare a British Standard Specification for Vulcanized Fibre.

Preparation of the Electrical Vocabulary is making steady progress and one Section of this, namely, "Radio Communication," has already been published as a separate document (B.S.S. No. 166).

(40) International Electrotechnical Commission.

A meeting of the Council of the Commission was held in Paris in December 1923, when Dr. C. O. Mailloux was elected Honorary President. Signor Guido Semenza was elected the new President and Colonel Crompton was re-appointed Honorary Secretary.

The Council of the Commission have appointed an Executive Committee consisting of the President of the Commission, the Honorary President, the Honorary Secretary and three Vice-Presidents. This Executive Committee will meet twice a year and assist the Central Office in co-ordinating the work of the National Committees.

(41) Benevolent Fund.

The Committee of Management of the Benevolent Fund of the Institution report that on the 31st December, 1923, the Capital Account of the Fund stood at £9 969 11s. 3d., and the accumulated income at £1 622 17s. 6d. The donations and subscriptions to the Fund in 1923 amounted to £636 10s. 1d.

In the course of 1923, 52 grants were made to 21 persons, amounting to a total of £1 034 2s. 4d.

With a view to stimulating and sustaining the interest of all members in the Fund it has been decided to publish in future each month in the *Journal* of the Institution a list of the contributions received during the previous month, together with the names of the contributors.

(42) Annual Accounts.

Excess of Income over Expenditure.—After making provision for contingencies as in the previous year, there is a margin to the good on the Revenue Account for 1923 of £3 957 11s. 7d. This amount, which has been carried to the credit of the General Fund, compares with £862 2s. 8d. in 1922, an increase of £3 095 8s. 11d.

Mortgages.—

	£	s.	d.
In the Accounts for 1922 these stood at	20 338	6	5
Amount of repayments during the year	5 536	7	1
They now stand at	£14 801	19	4

Assets.—Taking the Tothill-street property and the investments at cost, and the Institution building and lease, the library and furniture, etc., at the values standing in the books after writing off depreciation,

	£	s.	d.
the Assets amount to	130 437	9	11
against Liabilities	5 038	6	11
leaving a surplus of	£125 399	3	0
which, in comparison with that of the year 1922, viz.	114 399	2	1
shows an improvement of	£11 000	0	11

The balance of £125 399 3s. 0d. is made up as follows:—

Assets.

	£	s.	d.	£	s.	d.
Properties.						
Institution Building and Tothill-street Property	92 289	3	11			
Less Mortgages ..	14 801	19	4			
				77 487	4	7
Investments, Cash, etc.				44 867	15	9
Stock of Paper, Libraries and Furniture ..				8 082	9	7
				£130 437	9	11
Less *Liabilities.*						
Trust Fund Income Accounts	416	0	0			
Sundry Creditors ..	3 669	19	10			
Repairs Suspense Account	563	16	6			
Subscriptions received in advance	388	10	7			
				5 038	6	11
				£125 399	3	0

(43) The Institution and Bodies on which it is represented.

Appendix D shows in diagram form the organization of the Institution and the bodies on which it is represented.

APPENDIX A.

Membership of the Institution.

The changes in the membership since 1st April, 1923, are shown in the following table:—

	Hon. Mem.	Mem.	Assoc. Mem.	Grad.	Studt.	Assoc.	Total.	Total.
Totals at 1 April, 1923	10	1 849	4 735	1 056	2 869	392		10 911
Additions during the year:—								
Elected	..	14	74	147	661	5	901	
Reinstated	..	3	13	4	29	2	51	
Transferred to	1	44	76	92	..	1	214	
Total	1	61	163	243	690	8	1 166	
Deductions during the year:—								
Deceased	1	22	21	1	3	7	55	
Resigned	..	10	27	11	46	4	98	
Lapsed	..	15	74	52	138	16	295	
Transferred from	..	1	43	37	128	5	214	
Total	1	48	165	101	315	32	662	
Net Increase		..	..	..	..	..	..	504
Totals at 1 April, 1924	10	1 862	4 733	1 198	3 244	368		11 415

APPENDIX B.

Meetings.

The following is a list of the meetings held during the past twelve months:—

Ordinary Meetings	18
Special General Meetings	2
Wireless Sectional Meetings	9
Informal Meetings	13
Council Meetings	15
Local Centres:—	
Irish	6
Mersey and North Wales (Liverpool)	8
North-Eastern	11
North Midland	9
North-Western	11
Scottish	6
South Midland	10
Western	10
Local Sub-Centres:—	
Dundee	8
East Midland	10
Sheffield	7
Tees-side	7
Students' Sections:—	
London	8
Birmingham	8
Leeds	13
Liverpool	9
Manchester	10
Newcastle	12
Scottish	5
Sheffield	7
Committees:—	
Benevolent Fund	6
Electricity in Agriculture	2
Electricity (Supply) Regulations	44
Committees (*cont.*):—	
Electricity in Mines	2
Electro-Chemistry and Electro-Metallurgy	3
Examinations (and Sub-Committee)	8
Finance (and Sub-Committee)	12
General Purposes	8
Informal Meetings	9
Library and Museum	2
Lighting and Power	3
Local Centres	5
Membership	8
Model General Conditions	3
Papers	8
Patent Law	2
Proving House	1
"Science Abstracts"	2
Ship Electrical Equipment (and Sub-Committee)	2
Telegraphs and Telephones	3
Traction	3
War Memorial	1
Wireless Section	6
Wiring Rules (and Sub-Committees)	20
Other Committees	13
Total	408

APPENDIX C.

THE ENGINEERING JOINT COUNCIL.

Established 1922.

The Engineering Joint Council has been formed under the following constitution by the following four Institutions:—

The Institution of Civil Engineers,
The Institution of Mechanical Engineers,
The Institution of Naval Architects,
The Institution of Electrical Engineers.

CONSTITUTION.

1. A Council to be entitled "The Engineering Joint Council" shall be formed. It shall consist of two members of the Council of each of the following Institutions in the first instance, appointed from time to time by their Councils severally:—

The Institution of Civil Engineers,
The Institution of Mechanical Engineers,
The Institution of Naval Architects,
The Institution of Electrical Engineers,

which shall be called the Founder Institutions.

2. The members of the Joint Council shall be appointed annually, and shall be eligible to serve for not more than four years consecutively. One of the first two appointed by each Institution shall serve for not more than two years, but shall be eligible for re-appointment for a further period of not more than four years consecutively.

3. The Chairman shall be elected annually by the Joint Council, and the Secretary of the Institution represented by the Chairman for the year shall act as Secretary of the Joint Council. The Chairman shall be chosen from the several Institutions in rotation.

4. The Joint Council shall consider matters referred to it by the Council of any one of the constituent Institutions. It shall not initiate proposals affecting the Institutions, and shall be an advisory body without executive powers.

The Engineering Joint Council have made the following Bye-Laws:—

BYE-LAWS.

I. Session and Meetings.

1. The Session shall commence on the 1st May of each year and continue until the 1st May of the following year.

2. At least two meetings in the year shall be held, one in November and the other in March, and additional meetings shall be held if and when considered desirable by the Chairman. At least two weeks' notice shall be given of the date upon which such meetings are to be held.

3. The Councils of the several Institutions forming the Joint Council shall be asked to nominate and communicate to the Secretary for that year, the names of their representatives on the Joint Council before the beginning of March in each year.

4. The Engineering Joint Council at the meeting in March shall elect the Chairman and appoint the Secretary for the Session commencing on the 1st May of that year.

5. At the commencement of the new Session the Secretary for the previous Session shall hand over to his successor in office all documents, books and papers relating to the Joint Council.

II. Proceedings of the Joint Council.

1. No decision, other than those provided for in Clauses 3 and 4 of this Section, shall be taken by the Joint Council on matters referred to them unless at least one-half of the Joint Council be present, and any decision to be effective must be confirmed at a subsequent meeting at which at least one-half of the Joint Council are present. Any such decision shall be communicated to the members of the Joint Council before the confirmatory meeting, and when confirmed shall be communicated to the Secretaries of the several Institutions represented on the Joint Council.

2. All matters other than those referred to in Clauses 3 and 4 of this Section shall be decided by a majority of those present and entitled to do so voting in favour thereof.

3. The Joint Council may admit other Institutions or Societies to representation on the Engineering Joint Council, provided that all the representatives on the Joint Council who are entitled to do so vote in favour of such admission and in like manner confirm such action at a subsequent meeting. The conditions under which any such Institution or Society shall be admitted, and the number of their representatives, if any, on the Joint Council, shall be determined by the Joint Council at the time of the admission of such Institution or Society.

4. The Engineering Joint Council may terminate the membership of any Institution or Society, admitted as in Clause 3 of this Section, if the representatives of all the other Institutions who are entitled to do so vote in favour of such a course, and in like manner confirm such action at a subsequent meeting.

5. The Joint Council shall have authority to make rules for its own guidance, provided they are not inconsistent with the Constitution and Bye-Laws.

III. The Secretary.

The Secretary shall keep all minutes of the meetings of the Joint Council, which shall be treated as confidential, and shall conduct the correspondence of the Joint Council.

IV. Expenditure.

Incidental expenses incurred by the Joint Council shall be defrayed by the Institution from which the Chairman and Secretary have been appointed for the time being, provided that the matter be brought up for consideration by the Joint Council year by year. The question of defraying extraordinary expenditure not included in the above shall be considered from time to time as it arises.

V. Withdrawal of an Institution or Society from the Engineering Joint Council.

Any Institution or Society may withdraw from membership of the Engineering Joint Council at the end of any sessional year, provided three months' written notice be given to the Secretary of the Engineering Joint Council by the Secretary of the Institution or Society concerned.

VI. Alteration of Bye-Laws.

No alteration or revision of the Bye-Laws shall become effective until it has received the approval of the Council of each of the Founder Institutions.

April 1923.

REPRESENTATION OF ENGINEERING INSTITUTIONS ON THE JOINT COUNCIL.

RULES.

The following Rules framed in accordance with the provisions of Section II, Clauses 3, 4 and 5, of the Bye-Laws, have been adopted by the Joint Council on 9th April, 1923 :—

1. For the purpose of admission to representation on the Joint Council, Institutions shall be grouped as follows :—

Group A.—Constituent Institutions, i.e. Institutions representing important branches of Engineering, who have adopted examinations or equivalent qualifications for admission to their corporate membership, and of which the number of corporate members is sufficiently large in the opinion of the Joint Council to justify admission to this Group. Institutions in this Group would have one representative on the Joint Council who will be entitled to vote.

Group B.—Affiliated Institutions, i.e. Institutions whose interests are already represented on the Joint Council (by reason of a large proportion of their members also belonging to the Founder Societies or to Constituent Institutions) and whose membership is not (in certain cases) necessarily confined to Engineers.

These Institutions shall have the right to refer questions to the Joint Council, who will invite a representative (who shall not, however, have a right to vote) to attend the meeting of the Joint Council at which such questions are under consideration.

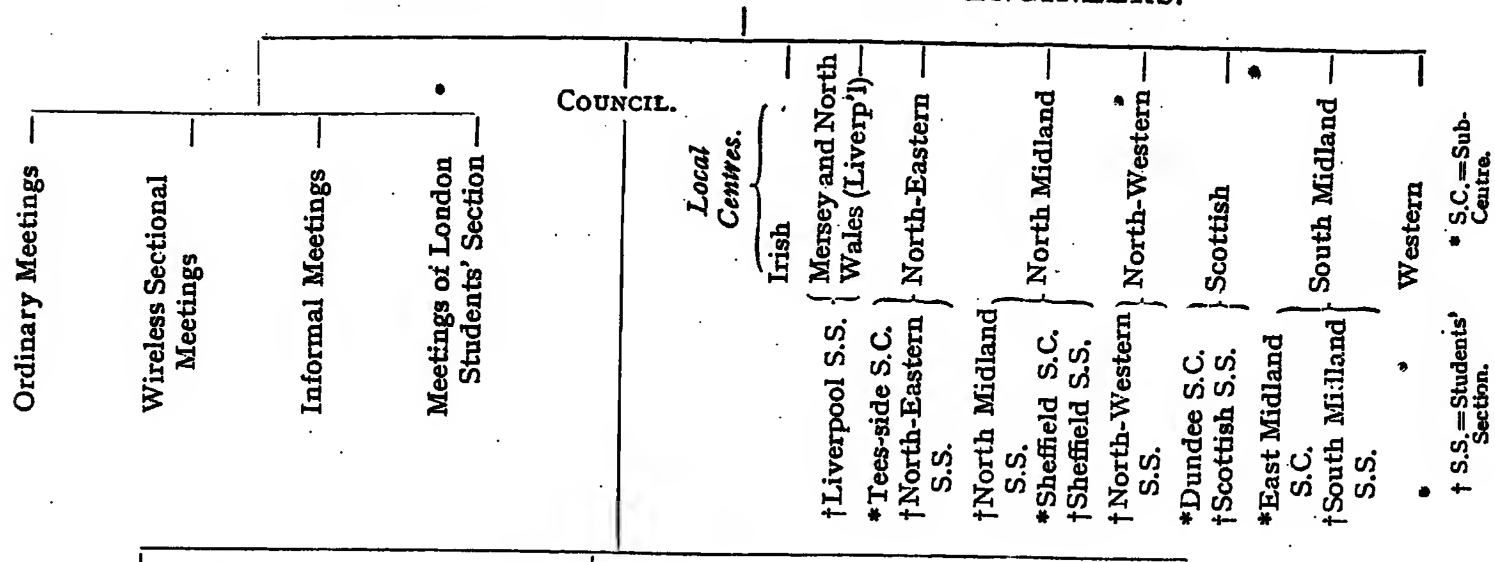
2. Institutions in Group B may be transferred to Group A (Constituent Institutions) when the standard of examinations and the number of corporate members justify such transfer in the opinion of the Joint Council.

3. Institutions desiring to be represented on the Joint Council shall make application directly to the Secretary of the Engineering Joint Council and not to the Secretary of any of the Founder Societies.

May 1923.

APPENDIX D.

THE INSTITUTION OF ELECTRICAL ENGINEERS.



Committees.
(*Standing.*)

Benevolent Fund
Electrical Appointments Board
Examinations
Finance
General Purposes
Informal Meetings
Library
Local Centres
Membership
Papers
Paul Scholarship
"Science Abstracts"
Ship Electrical Equipment
Wireless Section
Wiring Rules

Sectional Committees.
Electricity in Mines
Electro-Chemistry and Electro-Metallurgy
Lighting and Power
Telegraphs and Telephones
Traction

Committees.
(*Special.*)

Electricity in Agriculture
Electricity (Supply) Regulations
Examinations Sub-Committee
Model General Conditions
Patent Law
Proving House
War Memorial

Bodies on which the Institution is Represented.

Alloys of Iron Research (Royal Society)
Birmingham Chamber of Commerce
Bradford Public Libraries Committee
Bristol University
British Electrical and Allied Industries Research Association
British Empire Exhibition, 1924
British Engineering Standards Association
British National Committee of the International Electrotechnical Commission
British National Illumination Committee of the International Illumination Commission
Corrosion Research Committee of Institute of Metals
Darlington Board of Invention and Research
Electrical Development Association
Engineering Joint Council
Fifth International Road Congress, 1926
Franklin Institute Centenary Celebrations, 1924
Fuel Economy Committee of British Association
Imperial College of Science and Technology, Governing Body
Imperial Mineral Resources Bureau Conference
Institution of Civil Engineers, Engine and Boiler Testing Committee
Institution of Heating and Ventilating Engineers, Utilization of Exhaust Steam and Waste Heat Committee
International Mathematical Congress, 1924
International Scientific Unions
International Testing Association
Kelvin Centenary, 1924 (Royal Society)
Leeds Civic Society
Leeds Municipal Technical Library Committee
Loughborough Technical College Advisory Committee
Metalliferous Mining (Cornwall) School, Governing Body
Middlesbrough Technical College
Mines Department, Electrical Storage Battery Locomotive Committee
National Committee for Physics (Royal Society)
National Committee in Radio Telegraphy (Royal Society)
National Physical Laboratory, General Board
National Register of Electrical Installation Contractors
Newcastle-upon-Tyne Chamber of Commerce
Professional Classes Aid Council

(*Continued at foot of col. 1.*)

(*Continued from foot of col. 3.*)

Radiographers, Society of
Röntgen Society Advisory Committee for British X-Ray Industry
Royal Engineer Board
Royal Sanitary Institute Congress, 1924
Scientific and Industrial Research Advisory Council, Engineering Committee
Standing Joint Education Committee for National Certificates in Electrical Engineering
Transport, Ministry of, Advisory Panel
Union of Lancashire and Cheshire Institutes, Panel for Engineering
Women's Engineering Society
World Power Conference, 1924

THE INSTITUTION OF ELECTRICAL ENGINEERS.

REVENUE ACCOUNT FOR THE YEAR ENDED 31ST DECEMBER, 1923.

Dr. EXPENDITURE.

Year ended 31 Dec., 1922.* £ s. d.		£ s. d.	£ s. d.
	To MANAGEMENT :—		
	Salaries and Wages (including Staff Provident Scheme and War Bonus) ...	9 977 18 5	
	National Insurance	69 0 8	
	Audit Fee	42 0 0	
	Printing	736 10 3	
	Stationery and Office Requisites	345 5 10	
	Addressing	38 9 8	
	Postage of Correspondence and Notices	604 15 1	
	Telephone	66 4 2	
	Travelling Expenses	148 15 7	
	Bank Charges	23 17 6	
12,578 6 6			12,052 17 2
	„ INSTITUTION BUILDING :—		
	Ground Rent	2,201 0 0	
	Rates and Taxes	2,512 15 11	
	Heating	276 19 10	
	Lighting and Power	280 11 3	
	Insurance	163 7 11	
	Reserve for Repairs	600 0 0	
	Estate Agents' Fees	45 15 0	
	Household Requisites and Cleaning ...	223 16 10	
		6,304 6 9	
	Less Rents from Tenants	3,474 11 1	
4,422 6 11			2,829 15 8
990 12 10	„ INTEREST ON MORTGAGES		655 3 4
170 0 11	„ FURNITURE AND FITTINGS (Repairs and Renewals) ...		150 19 0
	„ JOURNAL :—		
	Printing	4,956 17 8	
	Postage	1,553 6 11	
	Wrappers and Envelopes	225 2 2	
		6,735 6 9	
	Ten-year Index 1912–21 (Cost of Printing, *less* Sales)	12 0 4	
		6,747 7 1	
	Less Sales and Advertisements... ...	2,575 19 1	
4,604 3 4			4,171 8 0
81 2 4	„ LENDING LIBRARY (Books, Printing, Postage, etc.) ...		108 8 9
420 19 1	„ EXPENSES IN CONNECTION WITH ROYAL CHARTER AND WINDING UP OF OLD INSTITUTION		135 15 6
	„ SCIENCE ABSTRACTS :—		
	Salaries, Abstracting, Printing, Postage, etc....	4,382 14 11	
	Less Subscriptions, Sales, and Advertisements	4,355 3 9	
1,084 14 11			27 11 2
	Carried Forward		£20,131 18 7

INCOME. **Cr.**

Year ended 31 Dec., 1922. £ s. d.		£ s. d.	£ s. d.
31,197 10 9	By SUBSCRIPTIONS		32,197 5 5
1,265 5 0	„ ENTRANCE FEES AND VELLUM DIPLOMA FEES		871 10 0
94 8 3	„ LIFE COMPOSITIONS		81 2 4
1,910 11 10	„ DIVIDENDS AND INTEREST		1,769 10 1
201 16 8	„ MODEL GENERAL CONDITIONS		247 18 3
11 17 6	„ WIRING RULES		3 14 0
6 10 0	„ SHIP ELECTRICAL EQUIPMENT REGULATIONS		8 11 4
	„ TOTHILL STREET PROPERTY :—		
	Rents from Tenants	1,282 8 8	
	Less Ground Rent, Repairs, Alterations, Rates, Taxes, etc.	392 9 6	
837 9 5			889 19 2
133 11 1	„ EXAMINATIONS (Fees, etc., less Expenses)		185 17 3
	Carried Forward		£36,255 7 10

REVENUE ACCOUNT—*continued.*

Dr. EXPENDITURE—*continued.*

1922*		£ s. d.	£ s. d.
	Brought Forward	... ...	20,131 18 7
	To INSTITUTION MEETINGS :—		
	Advance Proofs	130 13 2	
	Reporting	124 19 0	
	Grant to London Students' Section ...	32 14 6	
	Honorarium to Kelvin Lecturer	25 0 0	
	Refreshments, Assistance, etc.	230 1 2	
	Travelling Expenses of Authors of Papers	55 9 10	
931 7 9			598 17 8
	„ LOCAL CENTRES :—		
	Money Grants (including Travelling Expenses of Authors of Papers) ...	1,897 6 6	
	Travelling Expenses	512 14 10	
2,735 2 5			2,410 1 4
212 13 5	„ PREMIUMS FOR PAPERS	... ...	205 9 2
	„ SPECIAL GRANTS :—		
	British Engineering Standards Association	150 0 0	
	Electrical Research Association... ...	300 0 0	
	National Illumination Committee ...	40 0 0	
	Annual Tables of Constants and Numerical Data	26 5 0	
460 0 0			516 5 0
82 10 9	„ ANNUAL DINNER	... ...	94 19 5
500 4 2	„ CONVERSAZIONE...	... ...	507 13 9
94 17 6	„ LEGAL EXPENSES	... ...	51 10 0
78 6 2	„ MISCELLANEOUS EXPENSES	... ...	57 1 0
29,593 7 2			24,573 15 11
	„ AMOUNTS TRANSFERRED TO :—		
277 12 2	SINKING FUND (Premiums for Redemption of Cost of Building and Lease) ...	277 12 2	
3,000 0 0	RESERVE FUND (Contingencies and Mortgage Redemption)	4,500 0 0	
	GENERAL FUND :—		
94 8 3	Life Compositions received in 1923 ...	81 2 4	
993 13 6	Obligatory Repayment to Economic Life Assurance Society	1,036 7 1	
	Expenditure on—		
119 13 4	Books and Binding for Library ...	127 16 11	
718 3 5	Furniture, Fittings and Apparatus	1,701 1 10	
862 2 8	**Balance carried to General Fund** ...	3,957 11 7	
			11,681 11 11
35,659 0 6			£36,255 7 10

INCOME—*continued.* **Cr.**

1922		£ s. d.
	Brought Forward	36,255 7 10
35,659 0 6		£36,255 7 10

* This column does not add up to the total Expenditure shown, as some of the items in the Accounts for 1922 did not occur in 1923.

BALANCE SHEET, 31ST DECEMBER, 1923.

LIABILITIES.

	£ s. d.	£ s. d.
ECONOMIC LIFE ASSURANCE SOCIETY :—		
On Mortgage of Institution Building (1909) ...	26,000 0 0	
Since repaid	11,198 0 8	
	14,801 19 4	
On Mortgage of Tothill Street Buildings and Site (1910) £11,500 0 0		
Since repaid 11,500 0 0		
		14,801 19 4
„ KELVIN LECTURE FUND :—		
As per last Balance Sheet		648 13 0
„ UNINVESTED BALANCES OF TRUST FUNDS		416 0 0
„ SUNDRY CREDITORS		3,669 19 10
„ SUBSCRIPTIONS RECEIVED IN ADVANCE		388 10 7
„ REPAIRS SUSPENSE ACCOUNT :—		
Balance at 1st January, 1923	1,261 5 1	
Amount set aside in 1923	600 0 0	
	1,861 5 1	
Less Expenditure on Repairs in 1923... ...	1,297 8 7	
		563 16 6
„ RESERVE FUND (Contingencies and Mortgage Redemption) :—		
Balance at 1st January, 1923	14,000 0 0	
Amount transferred to Reserve Fund in 1923 ...	4,500 0 0	
	18,500 0 0	
Less Voluntary Instalment repaid to Economic Life Assurance Society on mortgage of Tothill Street Buildings and Site	4,500 0 0	
		14,000 0 0
Carried Forward		34,488 19 3

ASSETS. Cr.

	£ s. d.	£ s. d.
By INSTITUTION BUILDING AND LEASE :—		
Cost	73,028 6 10	
Less Reserve for Depreciation, being Surrender Values of Sinking Fund Policies	4,387 14 4	
		68,640 12 6
„ SINKING FUND (Surrender Values of Policies for Redemption of Cost of Building and Lease)		4,387 14 4
„ TOTHILL STREET BUILDINGS AND SITE (at cost)		19,260 17 1
„ KELVIN LECTURE FUND INVESTMENT (at cost)* :—		
£694 16s. 9d. 5 % War Stock (1929–47)		648 13 0
„ LIBRARY (exclusive of the Ronalds Library and Faraday Papers, which are held in trust) :—		
As per last Balance Sheet	1,049 14 8	
Additions in 1923	127 16 11	
	1,177 11 7	
Less Depreciation (10 %)	117 15 2	
		1,059 16 5
„ THOMPSON MEMORIAL LIBRARY (Contribution towards purchase)		1,000 0 0
„ FURNITURE, FITTINGS, AND APPARATUS :—		
As per last Balance Sheet	4,022 11 4	
Expenditure in 1923	1,701 1 10	
	5,723 13 2	
Less Depreciation (5 %)	286 3 8	
		5,437 9 6
„ MUSEUM (Instruments purchased from the collection of the late Sir William Crookes)		213 12 6
„ SUNDRY DEBTORS		3,285 18 1
„ INSURANCE PREMIUMS AND SUNDRY PAYMENTS IN ADVANCE ...		750 12 1
„ STOCK OF PAPER, ETC., FOR PUBLICATIONS		371 11 2
Carried Forward		105,056 16 8

BALANCE SHEET—*continued.*

Dr. LIABILITIES—*continued.*

	£	s.	d.	£	s.	d.
Brought Forward				34,488	19	3
To GENERAL FUND :—						
Balance at 1st January, 1923	99,750	9	1			
Life Compositions received in 1923	81	2	4			
Obligatory Repayment to Economic Life Assurance Society	1,036	7	1			
Voluntary Instalment repaid to Economic Life Assurance Society...	4,500	0	0			
Expenditure in 1923 on—						
Books and Binding for Library	127	16	11			
Furniture, Fittings and Apparatus	1,701	1	10			
Balance from Revenue Account for 1923 ...	3,957	11	7			
	111,154	8	10			
Less Depreciation (*per contra*) :—						
Library £117 15 2						
Furniture, Fittings, and Apparatus 286 3 8						
	403	18	10			
				110,750	10	0
				£145,239	9	3

P. D. TUCKETT,
Honorary Treasurer.

P. F. ROWELL,
Secretary.

ASSETS—*continued.* **Cr.**

	£	s.	d.	£	s.	d.
Brought Forward				105,056	16	8
By GENERAL AND RESERVE FUNDS INVESTMENTS (at cost)* :—						
£2,600 Natal Zululand Railways 3 % Debenture Stock	2,270	12	0			
£1,500 London, Midland and Scottish Railway 4 % Preference Stock	1,513	10	4			
£2,000 Assam Bengal Railways 3 % Stock (1931 or after)	1,548	0	6			
£750 Western Australia 4 % Stock (1942–62) ...	730	8	3			
£750 Union of South Africa 4 % Stock (1943–63) ...	742	12	0			
£750 Madras and Southern Mahratta Railway 4 % Debenture Stock (1938)	738	15	6			
£35 East Indian Railway "B" Annuity (1953) ...	791	5	4			
£1,500 South Australia 4% Stock (1940–60)	1,494	10	6			
£5,250 5 % War Stock (1929–47)	4,987	10	0			
£2,000 5 % National War Bonds (1929)	2,000	0	0			
£3,000 5 % National War Bonds (1928)	3,206	11	0			
£19,375 4 % Funding Loan (1960–90)	15,500	0	0			
£2,000 5¼ % Exchequer Bonds (1925)	1,991	9	0			
				37,515	4	5
„ CASH IN HANDS OF LOCAL CENTRES ON 30 SEPT., 1923				675	0	8
„ CASH :—						
At Bankers'	1,871	18	1			
In hands of Secretary	120	9	5			
				1,992	7	6
				£145,239	9	3

* The above values are subject to depreciation.

We beg to report that we have audited the Balance Sheet of The Institution of Electrical Engineers, dated 31st December, 1923, and above set forth, together with the annexed Statements of Account. We have obtained all the information and explanations we have required. In our opinion the Statements are correct, and the Balance Sheet is properly drawn up so as to exhibit a true and correct view of the state of the Institution's affairs according to the best of our information and the explanations given to us and as shown by the books of the Institution.

ALLEN, ATTFIELD & Co., *Auditors,*
Chartered Accountants,
24, MARTIN LANE, CANNON STREET, E.C. 4.

24th April, 1924.

SALOMONS SCHOLARSHIP TRUST FUND.

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	2,126 19 3	By Investments (at cost):—	
		£1,500 New South Wales 3½% Stock (1924) ...	1,556 5 9
		£500 Cape of Good Hope 3½% Stock (1929–49)	570 13 6
	£2,126 19 3		£2,126 19 3

SALOMONS SCHOLARSHIP TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholars in 1923	62 10 0	By Balance (as per last Account)	40 14 11
„ Balance carried to Balance Sheet *	48 5 0	„ Dividends received in 1923	70 0 1
	£110 15 0		£110 15 0

DAVID HUGHES SCHOLARSHIP TRUST FUND.

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	2,000 0 0	By Investment (at cost):—	
		£2,045 Staines Reservoirs 3% Guaranteed Debenture Stock (1922 or after)	1,998 15 0
		„ Balance carried to Balance Sheet *	1 5 0
	£2,000 0 0		£2,000 0 0

DAVID HUGHES SCHOLARSHIP TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholars in 1923	55 0 0	By Balance (as per last Account)	51 14 0
„ Balance carried to Balance Sheet *	58 8 4	„ Dividends received in 1923	61 13 10
		„ Interest do. do.	0 0 6
	£113 8 4		£113 8 4

PAUL SCHOLARSHIP FUND.

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	500 0 0	By Investment (at cost):—	
		£625 4% Funding Loan (1960–90)	500 0 0
	£500 0 0		£500 0 0

PAUL SCHOLARSHIP FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount paid to Scholar in 1923	37 10 0	By Balance (as per last Account)	37 10 0
„ Balance carried to Balance Sheet *	25 0 0	„ Dividends received in 1923	25 0 0
	£62 10 0		£62 10 0

* Included in the total of £416 0s. 0d. shown on the Liabilities side of the Balance Sheet.

WILDE BENEVOLENT TRUST FUND.

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	2,798 10 2	By Investments (at cost) :—	
		£1,308 London and North Eastern Railway 4% First Guaranteed Stock...	1,744 3 11
		£100 London County 3½% Consolidated Stock (1929 or after)	101 8 6
		£250 New South Wales 4% Stock (1942–62) ...	251 6 0
		£100 3½% War Stock (1925–28)	94 8 8
		£100 5% War Stock (1929–47)	95 0 0
		£381 15s. 1d. 4% Funding Loan (1960–90) ...	300 0 0
		£200 5% National War Bonds (1928)	211 11 0
		„ Balance carried to Balance Sheet *	0 12 1
	£2,798 10 2		£2,798 10 2

WILDE BENEVOLENT TRUST FUND (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Balance carried to Balance Sheet *	182 9 7	By Balance (as per last Account)	79 15 5
		„ Dividends received in 1923	99 18 0
		„ Interest do. do.	2 16 2
	£182 9 7		£182 9 7

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1).

Dr.	£ s. d.	Cr.	£ s. d.
To Amount (as per last Account)	1,700 0 0	By Investment (at cost) :—	
		£2,000 5% War Stock (1929–47)...	1,700 0 0
	£1,700 0 0		£1,700 0 0

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1) (Income).

Dr.	£ s. d.	Cr.	£ s. d.
To Grants made in 1923	150 0 0	By Balance (as per last Account)	150 0 0
„ Balance carried to Balance Sheet *	100 0 0	„ Dividends received in 1923	100 0 0
	£250 0 0		£250 0 0

* Included in the total of £416 0s. 0d. shown on the Liabilities side of the Balance Sheet.

THE BENEVOLENT FUND OF THE INSTITUTION OF ELECTRICAL ENGINEERS.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR 1923.

Dr. EXPENDITURE.

		£ s. d.
To Grants	£1,034 2 4	
Less previous Grants refunded	103 0 0	
		931 2 4
„ Printing, Stationery, Bank Charges, Postage, etc.		25 8 0
„ Unexpended Balance carried to Balance Sheet		159 16 3
		£1,116 6 7

INCOME. **Cr.**

	£ s. d.
By Dividends on Investments	470 12 9
„ Interest	9 3 9
„ Annual Subscriptions	231 1 6
„ Donations of £5 and over	178 14 0
„ Donations under £5	226 14 7
	£1,116 6 7

BALANCE SHEET, 31ST DECEMBER, 1923.

Dr. LIABILITIES.

		£ s. d.
To Capital Account:—		
As per last Balance Sheet		9,969 11 3
„ Income and Expenditure Account:—		
As per last Balance Sheet	£1,463 1 3	
Unexpended Balance in 1923	159 16 3	
		1,622 17 6
„ Sundry Creditors		37 4 5
		£11,629 13 2

ASSETS. **Cr.**

		£ s. d.
By Investments (Capital), at cost:—		
£961 7s. 7d. Cape of Good Hope 3 % Stock (1933–43)		950 0 0
£593 1s. 7d. New South Wales 3 % Stock (1935)		600 0 0
£420 London and North Eastern Railway 4 % First Preference Stock		503 18 3
£450 London, Midland and Scottish Railway 4 % Debenture Stock		551 0 9
£750 East Indian Railway 3½ % Debenture Stock		737 18 0
£300 London, Midland and Scottish Railway 4 % Guaranteed Stock		333 11 6
£500 New Zealand 3½ % Stock (1940)		486 18 6
£500 Canada 3½ % Stock (1930–50)		478 16 0
£1,126 6s. 3d. 5 % War Stock (1929–47)		1,067 6 6
£350 New South Wales 4 % Stock (1942–62)		336 18 6
£200 3½ % War Stock (1925–28)		188 17 3
£2,128 8s. 6d. 4 % Funding Stock (1960–90)		1,624 2 0
£2,000 5 % National War Bonds (1928)		2,110 4 0
		9,969 11 3
„ Investment (Income) at cost:—		
£1,000 5 % War Stock (1929–47)		1,002 19 3
„ Sundry Debtors		9 15 6
„ Cash:—		
At Bankers'	£611 0 10	
In hand	36 6 4	
		647 7 2
		£11,629 13 2

I have audited the above Balance Sheet and Income and Expenditure Account with the Books and Vouchers and certify them to be correct, and have verified the Investments with Certificates from Bankers. The Investments, which are stated at cost, are subject to depreciation.

24th April, 1924.

JAS. ATTFIELD, F.C.A.,
Honorary Auditor.

DEVELOPMENT OF THE BELLINI-TOSI SYSTEM OF DIRECTION-FINDING IN THE BRITISH MERCANTILE MARINE.

By Commander J. A. SLEE, C.B.E., R.N. (Ret.), Member.

(*Paper first received* 17*th August*, 1923, *and in final form* 19*th January*, 1924; *read before the* WIRELESS SECTION 5*th March*, 1924.)

SUMMARY.

The paper gives an account of the various sources of error which have been encountered during the development of the Bellini-Tosi system of wireless direction-finding as an aid to navigation in the British mercantile marine. These errors can be isolated and their causes removed one by one.

The application of the instrument to the purposes of navigation is also dealt with, and the possible errors, external to the ship, which may be encountered are considered.

A table is attached showing the high degree of accuracy which has now been attained.

(1) RETROSPECT.

The following notes concern the development of direction-finding on the Bellini-Tosi system, in which two fixed loop aerials at right angles to one another are used in conjunction with a rotatable search coil. The results mentioned have been obtained with spark (as opposed to continuous-wave or interrupted continuous-wave) telegraphy.

The first attempts were made with loop aerials, each tuned independently to the frequency of the signal the direction of which it was desired to obtain, the loop aerials being very loosely coupled to the search coil and its circuits. This system, which had given admirable results on land, was found when fitted in an iron ship to be too difficult to work and to possess too grave errors of a quadrantal nature to be of practical value for navigational purposes, the only justification for its existence in the mercantile marine.

The method of using untuned loops, usually, though incorrectly, called aperiodic loops, was then resorted to, and promising results were at once obtained.

(2) ERRORS ENCOUNTERED.

(*a*) *Calibration error.*—In all that follows, the word "loop" is used to convey the idea of the whole arrangement used to absorb energy from the ether, including the field coil, lead-covered cable and junction boxes, as well as the simple loop itself. The capacity present in this circuit is a complex quantity, of which the greater part is the capacity between core and core of the lead-covered cable. Such a circuit has a well-marked natural frequency. The expression "simple loop" is used to denote that portion of the whole which is purposely opened out so as to enclose a considerable area.

An analysis of the nature of the errors obtained when identical loops were used brought forward the fundamental conception on which all subsequent work has been based; that is to say, the idea that the ship herself with all her rigging might be imagined to be replaced by a fictitious simple loop lying in the vertical plane and parallel to the keel line of the vessel. The action of this fictitious simple loop is taken into consideration when determining the area of the fore-and-aft loop of the complete direction-finder system.

Since this fictitious simple loop is fore-and-aft, and since its effects cannot be ignored or eliminated and must not be allowed to produce an effect equivalent to mutual induction between the two tangible simple loops of the aerial system, it is clear that one of the two tangible simple loops must be parallel to the fictitious simple loop, that is to say, fore-and-aft. Therefore the other tangible simple loop must be athwartships.

Since the tangible fore-and-aft simple loop is coplanar with the fictitious ship simple loop, there will be considerable coupling between these two, and therefore the current circulating round the tangible fore-and-aft loop will, under any given conditions, be greater in some geometrical proportion than would be expected from a consideration of the dimensions of the fore-and-aft loop alone.

If identical loops were used, the result of the above would be that the directions as observed would tend to be crowded towards the fore-and-aft line, the error being a maximum when the correct relative bearing is on the bow or quarter, and vanishing when the correct relative bearing is abeam, or ahead, or astern.

This error, which is now in practice usually given the name of "calibration error," can be completely removed by reducing the area of the tangible fore-and-aft loop, or by adding to its impedance, or by a combination of these two methods. It is usual in practice to employ the largest convenient thwartship loop (up to an area of about 400 sq. ft.), and to adjust the size of the fore-and-aft loop until a slight calibration error remains, finally removing it by adding impedance equally to the two limbs of the fore-and-aft loop.

(*b*) *Loop-tuning error.*—The previous paragraph shows that the two loops are essentially of different dimensions and therefore, in all probability, of different natural frequencies. If both the loops are very considerably different in frequency from that of the signal to be received, the current circulating in each will be almost in quadrature with the voltage applied by the incoming wave, and therefore the currents flowing round the two loops will be almost exactly in phase with one another. Further, the value of the current reached in each loop will be almost exactly proportional to the voltage applied to that loop by the incoming wave.

If the first of these two conditions (similarity of

phase of circulating currents) is not made good, the familiar rotating-field effect will be produced on the search coil. Since the position of zero coupling between the search coil and the field coils which are connected to the loops is the index by which directions are measured, the effect of such a rotating field is to fog the observation by obscuring the position of zero signals.

Also, if one loop happened to be of the same, or very nearly the same, frequency as the incoming wave, the circulating current round it would be greater, in proportion to the voltage applied, than the current in the other loop (by hypothesis of different frequency) and therefore less nearly in resonance with the incoming wave. Therefore the proportionality between impressed voltage and circulating current will be different in the two loops, and a quadrantal error similar in effect to calibration error will result. Its extent will vary with alteration of wave-length of the received signal, and will vanish if the frequency of the incoming wave is midway between the frequencies of the two loops. As such an error varies with wave-length, it is quite inadmissible. These two effects of one cause are in practice lumped together under the name of "loop-tuning error." They can be completely avoided by fitting loops of suitable dimensions in the first place, and are almost unheard-of in practice.

(*c*) *Lack-of-symmetry error.*—If we consider the current flowing in any part of a vertical loop under the influence of an incoming ether wave, it is clear that there are two distinct components. One is a circulating current round the loop. The cause of this current is as follows :—

If we imagine each half of the simple loop from apex to junction box to be replaced by its phantom vertical projection, the incoming wave will induce a voltage between the two ends of each phantom projection, the potential to which each of these four ends is raised at any instant, by effects of the incoming wave, being different. If the plane of the simple loop is not parallel to the wave-front, the voltages induced in the two phantom vertical projections will be unequal, and the difference between them is the useful voltage available for the production of a circulating current. For brevity, this current is in practice called the "loop current," and clearly the instantaneous value of the voltage causing it depends upon the height and distance apart of the phantom projections (in practice, the area of the loop) and the rate of change of intensity of electric and magnetic stresses caused by the incoming wave at the instant under consideration.

The other component is a simple alternating current flowing in both sides of the complete loop from the apex to the mid-point of the field coils, the actual current distribution being to a great extent governed by the capacity to earth of the various parts of the loop. For the sake of brevity this current is in practice called the "plain current," and the instantaneous voltage to which it is due is caused by the instantaneous value of the electric and magnetic stresses set up by the incoming wave.

Hence we see that the "loop" voltage and the "plain" voltage are in quadrature, the loop current leading or lagging relatively to the loop voltage in accordance with the electrical constants of the loop circuit, while the plain current will lead or lag relatively to the plain voltage in accordance with the electrical constants of the plain circuit.

If the construction of the loop and its attendant field coil is perfectly symmetrical electrically, the plain current will be equally divided between the two halves of the loop, and the effects of each half of the field coil on the search coil will neutralize one another.

Absence of this condition of symmetry is the most troublesome, the most common, and the most dangerous source of error. It is generally called in practice "lack-of-symmetry" error, and the satisfactory operation of direction-finders on board ship is almost entirely a question of the success with which causes tending to produce or accentuate this error can be counteracted.

In order to protect the insulation of the connections between the loops and the direction-finder instrument, and also the windings of the field coils themselves, from the effects of accumulated static charges or the induction due to transmission, the centre of each field winding was at first connected direct to earth. This direct connection accentuated the effects of lack of symmetry, and has since been replaced by a suitable inductive choke.

The causes of lack of symmetry are twofold: "permanent" lack of symmetry due to unequal distribution of any electrical dimensions between the two sides of a loop, which would result in unequal impedance in the two halves, measured from apex to mid-point; and "inductive" lack of symmetry due to re-radiation and/or induction from individual conducting portions of the ship's structure, which may have unequal effects upon the two halves of a loop. The effects of the former are apparent, irrespective of the strength of signals, but the effects of the latter increase with the strength of signals and are often only noticeable with very strong signals. This state of affairs appears to be explained as follows :—

Consider an athwartship loop which is inductively unsymmetrical, the relative bearing being considered to be right ahead. There is zero loop current in this loop, but the effect of inductive lack of symmetry is to cause an unequal distribution of plain current between its two halves, and therefore there is a magnetic coupling between the field coil and the search coil. The effects of this current may be too slight to deflect the resultant magnetic field through the field coils to any appreciable extent, and no error is then observable, but when the effect of the inductive lack of symmetry becomes sufficient to deflect the resultant magnetic field through the field coils the error begins to appear. There is, in short, a marked threshold effect observable in cases of inductive lack of symmetry. In cases of permanent lack of symmetry, the disturbance due to unequal distribution of plain current increases in the same proportion as the loop current, being due directly to the plain voltage and not to the effects of an outside conductor itself under the influence of the wave, and no threshold effect is observed. Inductive lack of symmetry is the source of the most elusive and the most dangerous errors which have been experienced in the application of direction-finding to navigation.

Having decided on the position of the loops, the next point is to decide on their form. This is a matter of but very little importance provided that extremes are avoided, but it is very desirable that there should be a pronounced geometrical apex to each loop. For sea-going work it is essential that the thwartship loop should have a well-marked apex, and it is advisable that the fore-and-aft loop should have one also. The reason is simple. Consider a flat-topped thwartship loop. If the vessel is on an even keel the top of the loop is horizontal and the electrical apex is in the centre of the horizontal limb. If now the ship heels over, even to a very small angle, the apex becomes the weather corner and symmetry is destroyed. The same applies, but in a less degree, to the fore-and-aft loop.

Lack-of-symmetry error is the only error which can make a bearing appear to be in the wrong quadrant, and lack of symmetry in the thwartship loop may well be sufficient to make a bearing appear to be on the wrong bow.

If it can be assumed that the loops are symmetrically rigged truly fore-and-aft and athwartships, and with the geometric axis of each loop directly over the point where the ends of the loop join its cable, and that they can be kept taut, then the possibility of errors due to lack of symmetry is reduced to a minimum; and as permanent lack of symmetry can be detected by easily applied internal tests of sufficient delicacy, the actual danger due to lack of symmetry in all its forms is zero.

Lack-of-symmetry error takes many forms according to its extent, and whether one or both loops are at fault. The strange diversity of results is hardly worth recording now that symmetry testing has been established, but it is worth noting that a combination of a slight lack-of-symmetry error and a slight electrostatic error often has the effect of leaving one zero accurate and sharp and the other very "woolly." It is sometimes necessary to accept this as a temporary measure, and to let well alone.

(*d*) *Plain tuning error*.—The remaining inherent error is due to the effects caused by the frequency of one loop, viewed as a simple plain aerial, being very nearly in tune with the incoming wave when the frequency of the other loop is somewhat less nearly in tune. This error is comparable with loop-tuning error and is negligible if loops of proper dimensions are used. The adoption of the inductive choke mentioned in the preceding paragraph renders the loops viewed as "plain" aerials practically aperiodic (in the true sense of the word) and is now almost unheard of. The effects are zero if perfect symmetry exists; if not, it accentuates the lack-of-symmetry error on certain waves. It is generally called "plain tuning error."

(*e*) *Electrostatic error*.—There are also two inherent instrumental errors. Of these the more important is the result of superposing the stray capacity coupling between the field coils and the search coil upon the magnetic coupling. The effect of this stray capacity coupling is to distort both positions of zero resultant coupling, and, although the line bisecting the angle between the observed zeros is at right angles to the proper zero due to magnetic coupling only, the presence of this error is detrimental to rapid and accurate work. It can be practically annihilated by the interposition of an earthed shield between the windings of the transformer connecting the search coil with the tuning condenser. It is most noticeable when the stray capacity is large in proportion to the tuning capacity, that is to say on the shorter waves, when the tuning capacity is very small. This is commonly called the electrostatic error.

(*f*) *Coupling error*.—The second instrumental error is due to the fact that as the search coil is rotated the coupling between the search coil and either of the field coils does not vary exactly in accordance with a cosine curve. By spreading out the windings of the search coil on one side of its former in a **V** shape, this error, which is never as much as 1°, can be made to reach its maximum and fall to zero eight times in the 360°, and so long as "swing" readings are used it is truly negligible, and in practice no notice is taken of it. This is the cause of the important difference in practical working between systems employing "tuned" and "untuned" loops. In the former case the arc through which the search coil can be moved, while still preserving inaudibility of a naturally good signal, is very small—perhaps only 2° to 3°—and under these conditions what are familiarly known as "sitting" readings can be taken. In the latter case the arc of inaudibility is usually 20°–40° and "sitting" readings are impossible; only swing readings can be used, and these of necessity eliminate the second instrumental error.

The colloquial term "swing readings" means observing the position of the pointer which gives equal strength of signals on either side of the arc of inaudibility, and taking the mean of these two positions as the position of true zero. It is usual to observe the position in which the signal just becomes inaudible. Bearings are perfectly reliable with vanishing points up to 60° apart.

(3) Construction of Loops.

From the foregoing it is clear that, given a properly constructed direction-finder, everything depends upon the erection of electrically symmetrical loops of the correct relative areas, the planes of the loops being necessarily vertical and at right angles to one another. One must be exactly fore-and-aft and the other exactly athwartships, but there is no reason why their planes should intersect, and no practical disadvantage is found if they do not do so, so long as the distance between their axes is small in comparison with a quarter wavelength.

It should be noted that there is no obvious theoretical reason why the fore-and-aft loop should be on the centre line of the ship, though common sense indicates that it is desirable to place it there. No experiments have been tried with fore-and-aft loops out of the centre line, as every effort has been concentrated on producing a seamanlike and trustworthy aid to navigation, and no opportunity has offered for academic investigation. One fore-and-aft loop accidentally fitted a little off the centre line gave indifferent results.

Under ordinary sea-going conditions a subsidiary difficulty is experienced. If the loops cannot be made permanent, but have to be lowered and re-hoisted

frequently, there is a great likelihood of the symmetry being destroyed in the process. This has been found to be a very real and serious cause of trouble.

Summarizing the above, it is clear that the main practical difficulty lies in the selection of a suitable position for the loops and in the appropriate arrangements for rigging them. Before selecting the position of the loops it is first necessary to decide on the position of the direction-finding instrument. As far as the mercantile marine is concerned, it is highly desirable to have the instrument in the wireless room. It should be under the charge of the telegraphist and always available for practice, and when using it he should be in his own place and not an intruder among the navigating staff. The position of the direction-finding instrument must to some extent limit the choice of positions for the loops, on account of the capacity of the connecting leads.

For this purpose twin lead-covered paper-insulated cable is used, the cores each consisting of one strand of 20 L.S.G. copper, and with this cable a total length of 100 feet is permissible from the direction-finder to the commencement of the loops. This figure is based on the assumption that the loops are to be large enough to allow good bearings to be obtained up to a distance of 100 miles on spark waves between 400 and 1 000 m, and small enough to avoid "loop-tuning" error on 400 m.

Experience shows that the larger the ship the larger should the loops be for a high degree of accuracy. Small loops, even down to an area of 70 sq. ft., have given accurate service at ranges up to 30 miles in small ships, though they are not accurate in large ships. The reason for this appears to be best explained if the state of the electric field among the rigging, funnel, boat gear, etc., of a large ship be regarded as a mass of eddies, in which loops large in proportion to their surroundings are affected by many such eddies tending to balance one another and thus give an accurate average result, whereas loops small in comparison with their surroundings are more likely to feel the effect of a single eddy and thus give inaccurate bearings.

Experience has shown that loops work well for all frequencies lower than their own natural frequency, but they are very unsatisfactory for frequencies higher than their own. Obviously, the capacity from core to core of the lead-covered cables is a very important factor in determining the "loop" frequency of each aerial, and the capacity from cores to lead covering is of similar importance in determining the "plain" frequency of each aerial. The core-to-core capacity also acts as a shunt to the field coils, and, briefly speaking, the shorter the cables the better are the results.

Having complied with the limits imposed by the permissible length of cable, a search must be made for some place where the loops can be erected and in which it will not be necessary to lower them. For work under mercantile marine conditions as outlined above (400 to 1 000 m spark), the area of the loops should lie between 200 and 400 sq. ft.

No part of the loop should come within 6 ft. of earthed metal, and if the disposition of such earthed metal is not symmetrical about the axis of the loop this distance must be increased to at least 12 ft. This figure is not yet definitely fixed, but there is clear evidence of evil effects at distances up to 10 ft., and it is quite possible that the safe distance may be as great as 20 ft.

If unsymmetrical objects, such as ventilators or hatches, are unavoidable, they must be screened by the interposition of an earthed plane—say wires 1 ft. apart —at least 6 ft. wide and symmetrically disposed on each side of the axis of the loop which it is intended to shield. Satisfactory results are obtained if the screen is midway between the nearest limb of the loop and the object from which it is to be shielded. If these precautions are neglected, evanescent errors may occur due to, for instance, the opening and shutting of large iron skylights, turning of ventilators, etc.

By far the best construction for loops, working within the limits of wave-length mentioned in this paper, is to support them on five light spars, so that the dimensions of the loop are about 8 ft. high by 30–40 ft. wide, the apex being about 6 ft. above the upper outer corners. Spars about 25 ft. long with

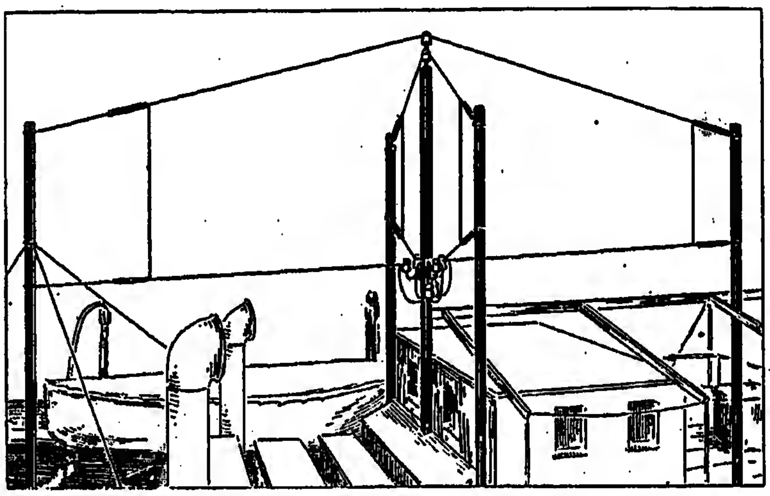


FIG. 1.—Direction-finder aerials supported on posts; s.s. "Motagua."

6-in. heel tapering to 4-in. heads will generally meet the case, or a bridge can take the place of one of the spars, or even of two of them. These spars must be placed with accuracy, the error of alignment of the sheaves not being allowed to exceed 1 in. Such an outfit can, as a rule, be made absolutely permanent, and is independent of changes of temperature and the working of the ship in a seaway. Figs. 1 to 3 show various methods of attaching aerials.

The insulation of the apex of the loops is not of very great importance, but at all other points at least a 10-in. surface should be provided.

Very considerable trouble has been experienced in the past due to injury to the lead-covered cable between the loops and the direction-finder instrument. These are now generally run in steel conduits. Armoured lead-covered cable has been tried, and is satisfactory if either the lead sheathing or the armouring can be earthed at intervals of not more than 20 ft.; but, on the whole, plain lead-covered wire in steel conduits is the most satisfactory.

The ends of the paper cable are protected by cast-iron bifurcating boxes of the usual commercial pattern.

When close to a compass wooden boxes are used. One of the minor difficulties of installing a direction-finder set in a ship is the protection of the ends of the paper-insulated cable from damp during the work of fitting.

After the loops are erected and have been proved to be geometrically correct and good for continuity and high insulation, they should be excited singly by a shunted buzzer as loops (not as plain aerials) and their wave-length checked. This should be below 400 m, preferably below 350.

The symmetry test should then be applied and, if the loops prove correct, the work of calibration can be commenced. But it is absolutely useless to attempt to calibrate until loop-tuning and lack-of-symmetry errors have been eliminated.

(4) Testing for Symmetry.

The principles on which a symmetry tester is arranged are as follows:

Consider a single loop with its field coil. Let this be excited as a "plain" aerial—say by means of a shunted buzzer connected to a straight lead between the mid-point of its field coil and earth. If the loop under test is symmetrical, current will be exactly divided between the two halves of the field coil and, consequently, there will be zero resultant magnetic coupling between the field coil and the search coil. There will be a certain electrostatic coupling between the field and search coils, which will be greatest when the search-coil windings are nearest to the field coil under consideration. If the search coil is turned round, clear signals will be heard in the telephones, and the strength of signals should be adjusted by means of the coupling to the shunted buzzer until they are just comfortably audible at the maximum positions. If, now, one side of the loop be disconnected—giving the maximum lack of symmetry—signals will become very much louder and will be audible nearly all round the scale. A very slight lack of symmetry will cause a magnetic coupling between the field and the search coils, which will have its maximum effect in the same position as the electrostatic coupling. As the magnetic coupling is dependent on the sense of the windings, and the electrostatic coupling is not, these two will be in conjunction in one position of the search coil and in opposition in the opposite position, a slight lack of symmetry being betrayed by the fact that the signals are not of equal strength when the pointer is at these two opposite positions on the scale.

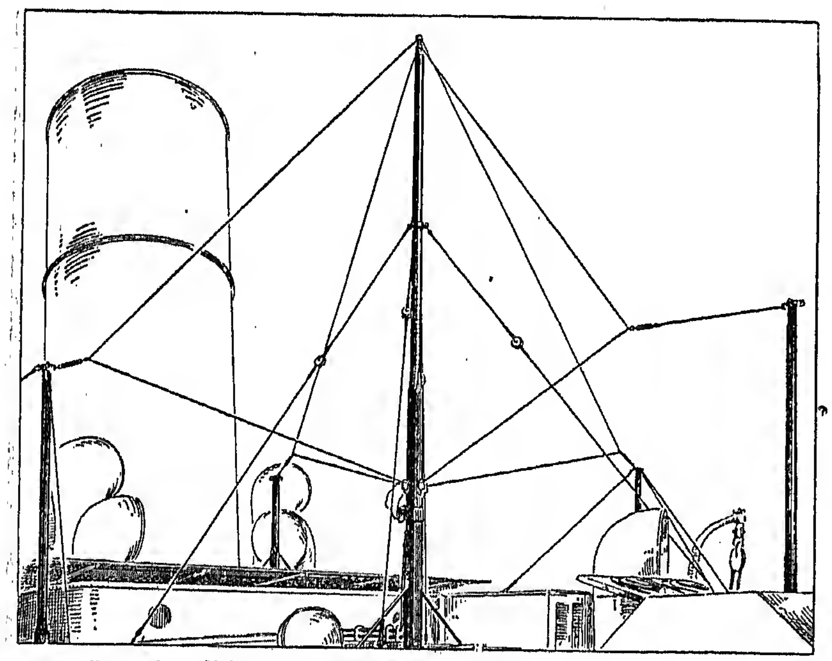


Fig. 2.—Direction-finder aerials fitted on posts; s.s. "Mooltan."

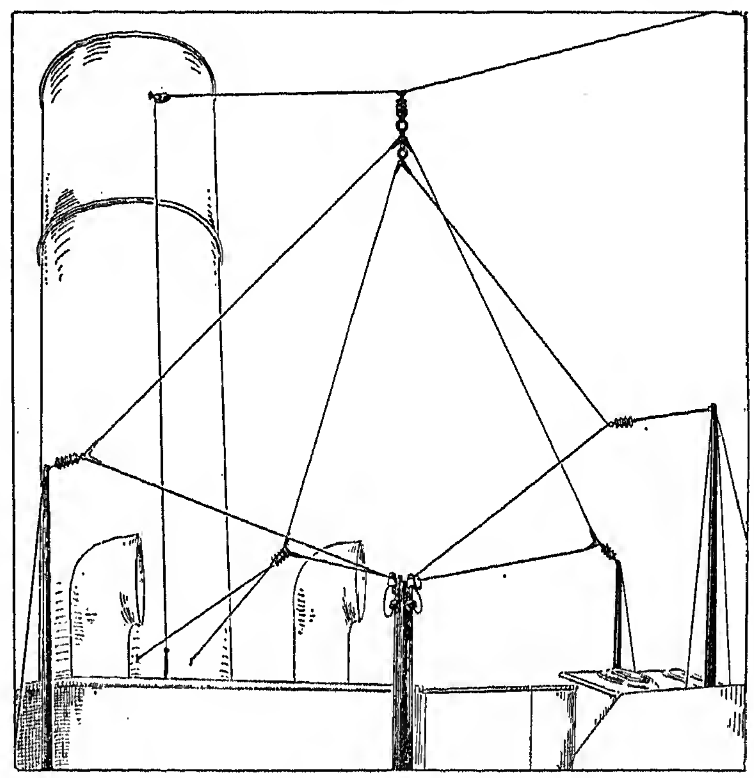


Fig. 3.—Direction-finder aerial hung from jumper stay.

When both loops are joined to their field coils and the whole system is excited through its common mid-point as above, it might be expected that signals would (under suitable conditions of buzzer coupling) be just audible when the search coil was exactly inside each field coil, so giving four positions of audibility at 0°, 90°, 180° and 270° (scale marked with 0° right ahead), but this is not the case, as the two combined electrostatic couplings have their maximum intensity at 45°, 135°, 225° and 315°. This is possibly a peculiarity of construction of the instruments with which all available experience has been gained.

Hence the result of exciting a pair of properly symmetrical loops is to produce zones of clearly audible signals when the pointer is near to 45°, 135°, 225°, 315°, with well-marked silent zones around 0°, 90°, 180°, 270°. If one of the loops is but very little out of symmetry the silent zone about one of these points is obscured, and signals at one pair of 45° are louder than at the other, with the result that signals become audible over a wide band about 0° and 180° (or 90° and 270°) with ill-defined minima between.

It has been found in practice that if the lack of symmetry is such that the zero is lost at 0°, 90°, 270° or 360° without destroying the perceptible maxima at the 45° positions, bearings will still be quite accurate when the mid-point is used unearthed, except for its static leak.

To sum up :—

(*a*) Perfect symmetry is indicated by signals of equal strength at the four 45° positions, with clear zeros between.

(*b*) Very slight lack of symmetry is indicated by signals at one pair of 45° positions being stronger than at the other pair, clear zeros still existing.

(*c*) Slight lack of symmetry is indicated by signals as at (*a*), but with the zero between the loudest positions obscured.

Bearings are still practicable under any of the above, provided that the mid-point is not earthed.

As the lack of symmetry becomes greater, the maxima at the 45° positions disappear, loudest signals appearing with the pointer at one of the 90° positions. In all cases signals are loudest when the search coil is under the field coil of the defective loop.

These symmetry tests are very critical and easy to apply. They disclose any doubtful contact or poor insulation, as well as uneven distribution of inductance or capacity. Unhappily, they do nothing towards the detection of inductive lack of symmetry of the magnitude likely to be met with at sea, which can only be tested for the observation of external bearings with very strong signals.

(5) Calibration.

Calibration is perfectly simple provided that the ship is well clear of cranes, sheds, etc. A station having a bow or quarter bearing should be selected, and if the observed bearing is too near the fore-and-aft line the fore-and-aft loop must be reduced—or the impedance increased—until the bearing is correct. If all other errors have been eliminated, the correction of a single bow or quarter bearing implies accuracy all round, but it is as well to take some check observations.

Under practical conditions the fore-and-aft loop is usually about four-fifths the area of the thwartship loop, and a reduction of 1 ft. on each side of the bottom of the fore-and-aft loop will produce a correction of about 1° in a bow or quarter bearing. Such figures are empirical and very rough, but they give some idea of the state of affairs.

Calibration can be carried out only on or very near the bow and quarter bearings.

The final external test is for inductive lack of symmetry, which should be carried out with very strong signals very nearly right ahead and on the beam. In the absence of errors due to this cause, the direction-finder can be trusted, but it must be remembered that the loops, and especially the lower parts, are almost as sensitive as a magnetic compass to the influence of external objects. A pile of Carless rafts placed temporarily under one limb of a loop, and a wet signal-halyard passing near one limb, have been recorded as producing errors of 5°, and a wire whistle-lanyard passing near one side of the fore-and-aft loop has been identified as the cause of an error of 14°.

It is well established that under conditions in which all the above can be eliminated, the errors of a Bellini-Tosi direction-finder need never exceed 1°.

When using a direction-finder in a ship at sea it is imperative that the main aerial shall be completely disconnected from earth. Otherwise, large errors of a quadrantal nature will be introduced. If the main aerial passes close to either of the loops it is not sufficient to disconnect between the transmitting apparatus and the earth connections; the main aerial must be disconnected immediately it enters the wireless room. The reason for this is that there is sufficient stray capacity in the transmitter to allow so much current to flow in the main aerial that the resultant "loop" current is affected.

Calibration cannot be completed if the ship is lying near to cranes or dock sheds, although an approximate result can be obtained. The work must be completed with the ship at sea.

The symmetry tester will reveal the impossibility of calibration. A pair of loops which give excellent results, and which test perfectly for symmetry when the ship is at sea, will appear to be hopelessly at fault if the ship is near to cranes, etc. The symptoms are different from those of slightly unsymmetrical loops—the usual effect being that the positions of all zero signals are slewed round bodily about 20°.

(6) Application.

Having established a direction-finder in correct adjustment, the problems of making full use of it as an aid to navigation can be tackled. The outstanding point is that a direction-finder takes relative great-circle bearings, that is to say, great-circle bearings relative to the keel line of the ship. These must be converted into true mercatorial bearings before they are of any use for navigation. If the ship is yawing, the observation of the direction of the ship's head at the moment when the bearing was taken may be rather vague. The usual practice is for the operator to ring a bell when the direction-finder bearing is taken and for the direction of the ship's head by compass to be noted when the bell rings; and considerable combined practice between bridge and wireless room is necessary before the gap between a good direction-finder bearing and a serviceable true bearing can be filled up.

Taking all the above into account, for the purpose of making up the attached tables bearings are reckoned as being "correct" if they do not err by more than 2° from that worked back from a recent position by observation, 1° being allowed for residual direction-finder errors and operator's observation, and 1° for errors developing in the operation of translating the direction-finder bearing into a true bearing.

Direction-finder bearings at distances of over 50 miles are not as a rule of any great service, and at distances over 100 miles they are only a rough guide. This is not because of the liability to error being increased, but because the fix so obtained is so very rough in comparison with older established methods of navigation.

The position is considerably improved in ships where a gyro-compass repeater is installed in the wireless room. In such cases a "true bearing indicator" is fitted whereby the bearing is read off on the face of the repeater instead of on the direction-finder scale, and the true bearing can be arrived at in one operation.

TABLE.

Record of Working of Ships' Direction-Finders.

Name of vessel	Date fitted	1 September to 31 December, 1921		1 January to 30 April, 1922		1 May to 31 August, 1922		1 September to 31 December, 1922		1 January to 30 April, 1923		1 May to 31 August, 1923		September to 31 December, 1923	
		Total	Correct	Total	Correct	Total	Correct	Total	Correct	Total	Correct	Total *	Correct *	Total *	Correct *
"Ballygally Head" ..	25/12/19	—	—	66	66	3	3	7	7	18	18	17	17	†	†
"Cassandra"	17/6/20	17	13	†	†	20	7	15	8	†	†	77§	60	24	21
"Empress of Britain" ..	1/9/22	—	—	—	—	—	—	86	73	†	†	46	39	18	15
"Fort Hamilton" ..	27/7/21	5	5	21	21	†	†	3	3	14	14	8	6	19	17
"Kenilworth"	21/7/21	9	8	15	14	15	15	5	5	9	9	Unfitted			
"Metagama"	6/10/22	—	—	—	—	—	—	22	21	32	24	49	48	92	90
"Montrose"	24/3/23	—	—	—	—	52	45	15	13	42	39	66	52	75	71
"Olympic"	15/12/20	—	—	14	14	3	3	†	†	†	†	†	†	3	3
"Rosalind"	14/5/21	32	31	13	13	44	44	31	31	41	41	30	30	58	54
"Saturnia"	2/7/20	‡	‡	†	†	33	32	10	10	7	7	13	13	23	23
"Tortuguero"	14/12/22	—	—	—	—	—	—	—	—	103	79	76	73	98§	73
"Vauban"	2/6/21	25	15	42	27	26	24	9	5	14	8	11	11	12	11
Totals for 99 ships		455	406	389	355	528	433	855	699	910	800	2 180	1 972	2 894	2 625
Percentage correct		89 per cent		91 per cent		82 per cent		82 per cent		88 per cent		90½ per cent		91 per cent	

* With reference to the last two columns, i.e. 1 May, 1923, to 31 Dec., 1923, the charts of bad bearing-arcs in St. Lawrence and English Channel districts were available, and bearings taken in these bad arcs are not included in the results given above.

† No reports received. ‡ Working satisfactorily. No details available. § Fault developed and removed.

For the first 6 months of 1924, reports were received from 69 ships showing:—

Total number of bearings taken	1 679
Total number of correct bearings	1 530
Total percentage correct..	91

It is obvious that the measurement of "direction" is in fact a measurement of the direction in which the plane of the advancing wave-front lies, and if this is not at right angles to the line of advance of the wave the direction as observed will be subject to error. Any such distortion of wave-front must introduce errors which cannot be detected at the receiver, and the well-known "land effect" and "night effect" are the common manifestation of this wave distortion. Night effect is generally accompanied by an unusual "woolliness" of zeros, but there is nothing to warn the observer of land effect except the general track of the wave when laid off on the chart. This is clearly the business of the navigating staff and not of the telegraphist, and more definite knowledge of the subject is required. Certain stations have a reputation for bad bearings, but there is not sufficient first-class evidence available to allow of a comprehensive statement being drawn up. It appears, in fact, as though land effect does not always occur, and certainly it varies considerably in extent. The general idea emerging from the records is that it occurs in two sets of circumstances:—

(a) When the line of bearing cuts a coast line—high or low—at an acute angle, say less than 20°; and

(b) When high land intervenes close to the receiver or transmitter.

It may be remarked that, so far, no effects have been associated with ice or fog banks.

An attempt has been made to overcome the difficulty of translating great-circle bearings into rhumb-line bearings by three methods: (1) Gnomonic charts are issued on which the great circles appear as straight lines; (2) a "half-convergency" table is issued from which the correction can be ascertained; (3) a "half-convergency" diagram is supplied from which the correction can be extracted. As a matter of navigation this correction is not of much value, as bearings at over 70 miles are seldom really used, and under 70 miles the correction is too small to be of any account.

It is worth noting that if two true bearings are laid off with station pointers on a gnomonic chart, the result amounts to a three-point fix, because the true north point forms the third bearing. When all is said and done, however, deep-sea navigation is not the most important zone of usefulness of a direction-finder.

The typical direction-finder as described gives an ambiguous result, there being no distinction between a bearing and its complement. In order to distinguish this point, direction-finder instruments are now fitted with a sense-finder, which is a form of the ordinary "heart-shape" receiver. As fitted in most ships the heart-shape diagram is by no means true and the zero not as a rule good, and it is only used as an indication.

It is doubtful whether this sense-finding is of much real use for fixing the position of a ship, but it is very useful when working through cross-traffic in fog and has sometimes been of great value in helping to pick up a vessel in distress which has been badly out of her reckoning and has announced a very bad position.

All remarks on direction-finding have so far been made with sole reference to spark telegraphy. Bearings taken of continuous-wave stations are very crisp and clear, but the wandering due to "night effect" takes place at times to so great an extent as to make bearings of continuous-wave stations quite useless for navigational purposes. This is usually the case after dark.

If a sense-finder is used, and if the plain component is balanced so as to give an accurate zero, then the position of that zero is not subject to wandering. The chief trouble lies in the fact that the rate of reduction in signal strength is not the same on both sides of zero, and therefore the position of zero is not midway between the vanishing points. Hence it is practically impossible to fix the position of zero of a continuous-wave signal with sufficient accuracy for navigational purposes.

The table on page 549 is a précis of the record progress made during the last two years in the adaptation of the direction-finder to the purposes of navigation in the mercantile marine. It consists of the details of the working of 12 ships taken at random from among 99, the totals for the whole 99 being shown at the foot of the columns. Some difficulty has been experienced in compiling this table, as reports are not perfectly regular and are not always fully detailed.

Bearings recorded as inaccurate include all causes of error, unless the direction-finder is definitely known to be out of action. "Night effect" is also included, but, since the approximate positions of "bad" areas have been promulgated, bearings which have been taken in known "bad" areas have been excluded from the list.

Discussion before the Wireless Section, 5 March, 1924.

Admiral of the Fleet Sir H. B. Jackson: The paper is almost supplementary to that recently read * by Mr. Horton on similar stations in the Navy. It is also supplementary to the numerous ones on errors in direction-finding stations on shore. These papers all point to this conclusion: if a direction-finding station is erected in a really good position on or very near the sea, well removed from masses of metal or from lengthy conductors, it can be depended upon to obtain accurate readings by day or night of the direction of a transmitting station at distances up to, say, 100 miles over sea, and this is independent of the type of receiving apparatus installed. I am frequently asked by shipowners and port authorities as to this, and that is the answer which I give them. I hope that the paper will enable those responsible for fitting ships and shore stations with direction-finding sets to make up their minds that they can safely do so, with the confidence that they will get good return for their expenditure;

* *Journal I.E.E.*, 1923, vol. 61, p. 1049.

but, on their part, they must allow the wireless experts a fair chance of correcting its errors and adjusting the set, just as much as they would in the case of their ship's compasses. I hope that the discussion will have the effect of enabling us to say whether continuous-wave transmission is as dependable as damped waves for direction-finding bearings directly over the sea, as the point is of great importance in view of the forthcoming International Conference on allocation of frequencies, decrements, etc., for direction-finding stations. It is difficult to understand why a continuous wave when passing over the open sea should be refracted either more or less than a damped wave of the same frequency. If it appears to be so, may not this be due to the method of reception, or to the environment of the loop, or to inadequate shielding from detached metallic masses on board, or to rolling or pitching, or, again, to changes in the conductivity of that fictitious loop formed by the ship's masts, rigging, rope gear, etc., which may have an adverse effect on the accuracy of bearings with any type of transmission? This cause of possible error has an important bearing on the point as to whether bearings had better be taken on board ship or taken on shore and signalled to the ship. There are evidently arguments in favour of each method, but I look forward with some confidence to the time when bearings will be taken on a ship without the necessity of employing special apparatus which may be affected by changes such as those mentioned by the author.

Mr. L. Bainbridge-Bell: I have followed the paper with great interest as I have been working for some time on similar problems. I have, however, always worked with rotating coils which move in the actual field due to the incoming waves, and not in an artificial field such as is used in the Bellini-Tosi system, and the main thing that strikes me on reading the paper is the number of possible causes of error liable to be introduced into the Bellini-Tosi system on account of the greater number of links in the chain between the incoming wave and the receiver—I mean the extra errors which can be introduced by the Bellini-Tosi aerials. By using rotating aerials the only correction which has to be applied is that for the quadrantal error, or, as the author calls it, the calibration error. There is one point which has not been mentioned, viz. the variation of this calibration error with the variation of draught of the ship. In the *Radio Review* for August and September 1920 the question of calibration error was examined theoretically by Commandant Réné Mesny. He treated the ship as a semi-cylinder with its axis on the water line, and he developed a formula which gave results agreeing with his observations. It would therefore appear that the calibration error is due only to that part of the ship which is above the water line. In a certain ship in which I carried out experiments, the maximum error on the bow (45° off the line of the ship) changed from 5° to 9° when the draught of the ship varied from 27 feet to 16 feet. I should like to know how this variation in error (which corresponds to the variation in the error of the fictitious loop of the author) would be allowed for in the Bellini-Tosi system. In a footnote to the table in the paper, mention is made of particulars of bad bearing-arcs in certain places in the St. Lawrence and in the English Channel. I am of the opinion that all ships experiencing definite bad errors of operation should, as a matter of routine, report them to the Mercantile Marine Department of the Board of Trade for insertion in Notices to Mariners. Finally, I should like to know if it has not been found that the bad bearings are more noticeable when the ship is close to the wireless station from which it has taken the bearing, and that these bad bearing-arcs vanish when the ship is at a great distance, say 200 miles, from the wireless station.

Professor C. L. Fortescue: With regard to the "swing" readings mentioned by the author, it appears that a "silence" zone covering 60° is very large for any reasonable degree of accuracy to be obtained. The most important point raised, however, is that which has already been touched upon by previous speakers, namely, the accuracy with which directions can be fixed by means of continuous-wave signals. Many of the difficulties to be expected from "beacon" stations would be eliminated if the continuous wave could be safely used. It has been suggested that the receiving apparatus is responsible for the observed errors, but even where the greatest care has been taken there seem still to be unexplained inaccuracies when working with continuous-wave stations.

Mr. R. Keen: Such a paper as this must of necessity be of the greatest interest to all who are concerned with direction-finding and wireless navigation at sea, and is of particular value in that the information is based on the actual experience with a hundred or more ships in which the Bellini-Tosi system has been operating under commercial conditions and with a satisfactory degree of accuracy. Some of the troubles experienced by the author in ships are common to land stations, and in the case of one coast direction-finding station that I have in mind, in which the Bellini-Tosi aerials had to be suspended from a steel jumper stay between two steel towers and over the roof of the station buildings, the re-radiation trouble was quite marked in the case of signals from ships using full power within a dozen miles or so. In such cases it was sometimes almost impossible to distinguish the minima, whilst in intervals between transmissions the more distant stations could be observed to have perfectly crisp zeros. Arising out of the addendum which the author has read this evening is a matter which seems to me to be of the greatest importance, and that is the choice of the type of transmitter to be used for direction-finding beacon stations. The continuous-wave transmitter would be infinitely more convenient, but experience shows that night variations of apparent bearing are definitely more marked on continuous waves than on spark signals. Captain H. J. Round, in his paper* read before the Wireless Section four years ago, said that he and his staff, who had been engaged upon direction-finding during the last 18 months of the war, were fully satisfied that there was more night effect in the case of continuous-wave stations than with spark stations, and whilst Admiral Sir Henry Jackson, in the discussion on the above paper, said

* *Journal I.E.E.*, 1920, vol. 58, p. 224.

that the battle of Jutland was indirectly brought about by the careful and accurate work of the direction-finding stations, it is interesting to note that the accurate work was all done on spark signals. The experience of direction-finding over sea since the war, has gone to confirm these views, and during this period we have had presented T. L. Eckersley's ingenious theory of the cause of night variations, experimental confirmations of which have also appeared in the technical Press. I should like briefly to outline this theory as it throws a good deal of light on the extraordinary variations of bearing which are often observed about the hour of sunset. The theory assumes the existence of the Heaviside layer, i.e. a horizontal layer of ionized air, the lower limit of which slowly rises, as the sun's light is withdrawn, to a height of roughly 80 to 100 km. This layer forms a reflecting and refracting medium for some of the energy radiated from a transmitting station, so that two paths exist from transmitter to receiver as in Fig. A. Now the wave which arrives at the receiver R by the direct path, and which we will call the "A" wave, must be normally polarized since any component of the wave having its lines of magnetic force vertical will be dissipated a few wave-lengths from the transmitter. A direction-finder at R will, therefore, always give a true bearing on the "A"

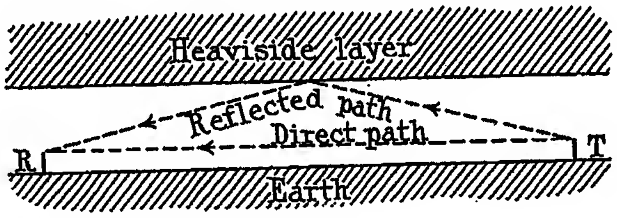


FIG. A.

wave. The reflected wave, since it is travelling in free space, may retain the degree of polarization peculiar to the transmitting aerial used, or, according to Dr. Eccles,* the polarization may be affected by the earth's magnetic field in conjunction with the ionized upper atmosphere. Eckersley now states that the reflected wave on reaching the receiver may be resolved into two components, one, which we may call the B component, being normally polarized, and the other the C component, which has its magnetic field in the vertical plane through the direction of propagation, and which is not necessarily in phase with the B component. A direction-finder at R will always give true bearings on the B component, but will always have a 90° error on the C component since a frame will have minimum linkage with the C wave magnetic flux when the plane of the frame coincides with the vertical plane of propagation between T and R, instead of when it is broadside on as in the case of a normally polarized wave. Under certain conditions of wave-length and lengths of the direct and reflected paths, the A wave and the B component of the reflected wave may be in exact phase opposition and equal in amplitude so that the only signal received is that due to the C component, with a consequent 90° error and reduction in signal strength. As the length of the reflected path increases due to the rising of the reflecting layer, the balance of the phase and amplitude of the A and B waves is destroyed, either the A or B components may preponderate, signals reach a normal night strength and the bearing is practically correct. Wright and Smith † have shown curves of bearings taken on Clifden station during the sunset period. These clearly illustrate the above phenomena and also confirm the marked fading of signal strength when the error in bearing is a maximum, although, owing to the transient nature of the factors producing the effect, it is only occasionally that the cycle is completed without some discontinuity occurring. These observations also show how the behaviour of the heart-shaped diagram of reception under the influence of night variations confirms the Eckersley theory. In the chapter on "Night Effect" in my book † I have shown a set of theoretical diagrams illustrating the effect, at a direction-finding station, of the resultant of the A, B and C component waves on the apparent bearing and signal strength, and it is interesting to note that the curves of error of bearing and signal strength and the sequence of crisp and indefinite direction-finding minima compare very closely with the observations of Wright and Smith. A further theoretical cycle of the heart-shaped diagram under similar conditions shows an equally striking similarity to the experimental results. A difference in apparent bearing of the marking and spacing wave of an arc station, which is not uncommon and may amount to 30°, is explained by the fact that whilst the condition of partial phase opposition of the A and B component waves may exist for one of the wave-lengths, allowing the C component to assert itself and produce an error, the phase conditions for the other wave may be such that the C component is entirely swamped by the normally polarized A and B components, giving the correct bearing. A number of other night-effect phenomena also fit in with the theory, and certainly no other satisfactory explanation of the facts seems forthcoming. In accepting the Eckersley theory, however, the important point is that we must also admit the probability that night effect will always be more marked on continuous-wave than on spark systems (in the existing commercial forms of direction-finding apparatus), because the latter consists of a broad spectrum of frequencies each section of which at any instant is at a different part of the above cycle, and only rarely will there be a large error with a crisp direction-finding minimum. Experience of direction-finding work over sea has shown that whilst crisp distorted bearings do occur on spark stations, particularly near the time of sunset, they are more common on continuous-wave signals, and the direction-finding operator using a spark beacon has the double advantage that the bearings will in general be more accurate at night and that when night effect is experienced there will be far more chance of the warning sign of the indefinite minimum. Up to distances of 80 miles and with a wave-length as high as 1 000 m it may be found that the night errors are not great, but I think that the evidence is quite convincing that the use of continuous waves for

* *Journal I.E.E.*, 1920, vol. 59, p. 77.

* *Radio Review*, 1921, vol. 2, p. 394.
† "Direction and Position Finding by Wireless."

beacons is very dangerous and should not be adopted until extensive trials have been carried out over sea. The adoption of spark beacons might cause interference with broadcast reception, but surely the interest of shipping and the safety of life must take precedence.

Dr. R. L. Smith-Rose: To one who has had considerable experience of all the practical systems of direction-finding, the first portion of the paper rather confirms the impression that the Bellini-Tosi system is complicated—far more complicated than any system using a simple loop or crossed-frame coil. The chief advantage that I have always appreciated in the Bellini-Tosi system was the fact that larger aerials were used than in the case of the single-loop system. I notice, however, that the aerials used on ships are as small as 70 sq. ft., and I think that with such small loops the frame coil can compete quite easily with the Bellini-Tosi system. With the use of a frame coil 4 ft. square, which would be quite good enough for ranges up to 50 or even 100 miles, four of the six errors mentioned in the paper would disappear immediately. The calibration error, which is inherent in the ship, would be of the same order and could either be read from a curve or compensated as in aircraft. The loop and plain tuning errors would disappear, and since there would be no goniometer the electrostatic and capacity errors would be eliminated. The lack-of-symmetry error could also be considerably reduced or even eliminated by the use of suitable screens. Thus a good case could be made out for the advantages of the frame coil as against the Bellini-Tosi system, and I believe that in the American ships the frame coil is used entirely for direction-finding. A point raised by Prof. Fortescue had reference to the angle of inaudibility, which, according to the author, ranged from 20° to 60°. In view of the fact that the author speaks of ranges of transmission to 50 miles, this has surprised me. This angle of inaudibility seems large, and with a swing of 60° it must be difficult to observe to the accuracy of 1°. Personally I do not like to take

TABLE A.

Table showing Results obtained in Observations on Spark and Continuous-wave Transmissions from Karlsborg.

Transmitting station	Receiving station	Type of transmission	Wave-length	Day observations			Night observations		
				Number	Total variation	Error of mean	Number	Total variation	Error of mean
			km		degrees	degrees		degrees	degrees
Karlsborg	Aberdeen	Spark	2·5	—	—	—	259	32·3	+ 7·6
Karlsborg	Aberdeen	C.W.	3·9	436	4·8	+ 1·2	242	34·3	+ 2·3
Karlsborg	Bangor	Spark	2·5	32	2·8	− 9·5	257	34·4	− 6·8
Karlsborg	Bangor	C.W.	3·9	540	10·8	− 5·2	291	51·1	− 4·1
Karlsborg	Birmingham	Spark	2·5	136	5·8	+ 0·6	438	47·5	+ 4·3
Karlsborg	Birmingham	C.W.	3·9	104	9·3	+ 1·7	38	7·5	+ 2·5
Karlsborg	Bristol	Spark	2·5	27	5·2	− 0·1	324	41·0	+ 2·5
Karlsborg	Bristol	C.W.	3·9	84	2·5	+ 1·3	23	11·9	+ 1·1
Karlsborg	Newcastle	Spark	2·5	171	6·6	+ 0·1	485	57·5	+ 5·1
Karlsborg	Newcastle	C.W.	3·9	503	10·5	+ 2·2	237	55·0	+ 3·8

TABLE B.

Results obtained on a Wave-length of 750 Metres.

Distance between transmitter and D.F. station	Type of transmission	Number of observations	Periods	Maximum error	Angles of swing used
miles				degrees	degrees
12	Spark	688	Day and night	0·8	1–2
12	I.C.W.	399	Day and night	0·7	0·4–2
12	C.W.	365	Day and night	0·9	0·4–2
98	Spark	119	Day	2·0	1–4
98	I.C.W.	89	Day	0·7	6–12
98	C.W.	73	Day	2·0	2–4
98	Spark	372	Night	12·0	Extremely variable with conditions
98	I.C.W.	189	Night	9·0	
98	C.W.	216	Night	11·0	

readings on the Bellini-Tosi system with an angle of swing greater than 5° each way. Judging from the table in the paper the author seems to have been very successful, in spite of the complicated nature of the system and of the several types of errors which he details. These various errors do seem to have been reduced to a reasonable quantity for practical working purposes. My own experience of the operation of a land direction-finding station has been that the limit of accuracy of 2° gives about 95 per cent of bearings correct when the range of transmission is from 10 to 100 miles. The next point of interest is in relation to the difference between spark and continuous-wave transmission. The statement as it appears in the paper is a very definite one, and I should like to inquire what evidence the author can produce to support it. The statement also seems definitely to ascribe the error on continuous waves essentially to a night effect. I am not sure that that is so; for early experience with continuous-wave direction-finding indicated that the errors were of an instrumental nature. Moreover, experiments have shown that very elaborate screening of the local oscillator is essential if any instrumental error is to be eliminated; but it *is* practicable to produce an oscillator which has no appreciable instrumental error and is available for use on any system of direction-finding in vogue to-day. I personally, working under the Radio Research Board, have operated 12 direction-finding stations in this country, all equipped for continuous-wave working. From the mass of data which I have obtained there does not appear to be any conclusive evidence that continuous waves are any worse than damped waves, other things being equal. Table A gives a specimen extract of these results showing the comparative errors experienced in observing on both damped and undamped wave transmission from Karlsborg. To decide finally if there is any difference, however, it is absolutely essential that the same transmitting station shall send out both the damped and the continuous waves from the same aerial on the same wave-length, and within a very short time—about 1 minute—of each other. Such test transmissions have been made from a special station set up at the National Physical Laboratory, and bearings were taken at two stations fitted with Bellini-Tosi direction-finders equipped for continuous-wave working on any wave-length from 300 metres upwards. A number of tests have been carried out in which a whole cycle of transmissions (spark, interrupted continuous-wave and continuous-wave) has been repeated every 10 minutes for 24 hours, and Table B shows the maximum errors experienced when working on a wave-length of 750 metres. Over a short distance of 12 miles nearly 100 per cent of the bearings are obtained within 1° on all types of transmission, and no difference between day and night working is observed. Over the longer distance of 98 miles, the errors are somewhat greater by night than by day, but it will be seen from the table that the errors are of the same order whichever type of transmission is employed. In view of the remarks which have been made in regard to the angle of inaudibility it may be interesting to point out the angle at which we usually work, as shown in Table B above. At a distance of 12 miles the angle of swing employed is from 1° to 2° on spark systems, from 0·4° to 2° on interrupted continuous-wave systems, and from 0·4° to 2° on continuous-wave systems. With the type of goniometer which we are now using it is extremely difficult to read the instrument with an accuracy of 0·2°. I should like to refer to one or two points which Mr. Keen has introduced into this discussion. His exposition of the Eckersley theory is good, but it leaves me entirely unconvinced. He made the statement that other observers had obtained very large errors on continuous waves, although the bearings were always perfectly sharp. My experience is to the contrary; the bearing minima frequently get blurred and appear to wander just as frequently on continuous waves as on spark. Mr. Keen also spoke of 180° rotations on continuous waves as being frequent occurrences, and that on 2 000 m an observation was made in which the bearing was thus rotated 3½ times round the compass. Out of the whole of the 140 000 readings which have been taken within our experience on wave-lengths from 450 to 9 000 metres, no error has exceeded 90°. We may have been particularly fortunate, but in view of the large number of bearings which have been taken there seems little to confirm Mr. Keen's suggestion. Another point mentioned by Mr. Keen was with regard to errors of the bearings originating from the transmitter. Some evidence has been produced by previous experimenters in this subject with regard to transmitting stations which are supposed to radiate waves with a vertical component of magnetic field as well as those with only a horizontal magnetic field. Observations which we have taken on well-known transmitting stations have shown no variation with the orientation of the direction-finder around the station, and there are also other reasons which go to prove that the transmitting aerial does not have any great effect on the errors in bearing. I should like to confirm the experience of the author as to the absence of effect from fog banks. I emphasize this point as some of the national regulations published give a warning as to the unreliability of bearings observed during foggy weather. In regard to areas of bad bearing, it would be interesting to know if the bearings taken outside the arcs which are marked "good" are always varying or whether there is merely a constant error. At one of our direction-finding stations when taking observations on another transmitter we have come upon a constant error of 3°, the station being at a distance of 16 miles, but there is never any variation in that error.

Major B. Binyon: Dr. Smith-Rose has mentioned the fact that among the advantages of using simple loops in preference to the Bellini-Tosi system is the fact that four of the errors mentioned in the paper are eliminated. He also referred to the fact that the Americans are using loops exclusively on ships. In addition, however, some British ships also employ loop reception on the Robinson system. There is a further advantage of the loop to which I should like to draw attention. The author says: "If the loops cannot be made permanent, but have to be lowered and re-hoisted frequently, there is a great likelihood of the symmetry

being destroyed in the process. This has been found to be a very real and serious cause of trouble." With the small loop this further source of error is entirely eliminated because it can always be installed in a permanent position and clear of derricks used for hoisting cargo. I must join issue with the author when he says, with regard to the position of direction-finding instruments: "As far as the mercantile marine is concerned, it is highly desirable to have the instrument in the wireless room. It should be under the charge of the telegraphist and always available for practice, and when using it he should be in his own place and not an intruder among the navigating staff." The wireless direction-finder is a navigational instrument and as such its proper place is among the other navigational appliances of a ship, either upon the bridge or in the chart room. Time and experience will show which is the best position, but the employment of small loop aerials enables the direction-finder to be installed either with the navigating instruments or in the wireless cabin. It is my opinion, however, that until masters and owners regard the directional equipment as a navigational instrument rather than a piece of wireless apparatus, its importance will not be fully appreciated, and for this reason I consider it desirable that the instrument should be placed in the navigational quarters.

Mr. M. Bennett: In the charts of error zones which the author has drawn up I suggest that at each transmitter there should be charted areas where errors occur due to the proximity of the ship to the transmitting aerial. It has been shown in some experiments carried out under the auspices of the Radio Research Board that near to an asymmetrical aerial there is a permanent error which is approximately equal to the angle subtended by the transmitting aerial at the direction-finder. There is therefore a liability of getting an error when broadside on to the transmitting aerial, the extent of which will depend on the distance of the direction-finder from the transmitter. Many ships coming into port will enter the region where this permanent error exists. But it is a perfectly definite error and a correction can therefore be easily applied to any particular case.

Mr. G. H. Nash: I have been impressed by the accuracy of the direction-finding results expressed in the paper, and am aware that amongst those who are interested in the safety of navigation at sea there is a growing demand that a system of wireless direction-finding should be given full support by the Board of Trade in order that their influence may be brought to bear on the actual adaptation of a system such as the one described by the author: and I have listened with interest to the opinion expressed by Admiral Jackson that this system should be adopted, but I feel that possibly the time is not yet ripe for the final determination of which system. It will be remembered that when the war broke out very little was known on the subject, and what little was known was naturally very much confined to the hands of those actually operating direction-finding apparatus during the war period. The system of operation at Admiralty stations during this period was not such as to encourage the most accurate work, because the various direction-finding stations only reported the bearings they obtained, and in the case of ships at sea it was left for another department of the Admiralty to determine the position after obtaining bearings from two or more stations. Further, as it was the position of an enemy ship that was involved, it was nearly impossible to check accurately the results obtained. There is no doubt that all non-wireless officers had very great belief in wireless direction-finding during the war, and it was on this belief that very definite statements regarding the position of enemy ships at various positions was made. It was not until after the war that light began to be thrown on the actual accuracy of direction-finding. It is stated on page 230 of vol. 58 (1920) of the *Journal* that the direction of Salonica would sometimes change by 90°, and that of Horsea by 30°. On page 238 it is suggested that a false confidence was gained by the "beautiful intersections" and it was only when shocks were received, such as when the wireless located the German fleet well inland, that any doubt was felt. Again, the immediate post-war literature shows other evidences of unreliability. In the *Radio Review* (1919–20, vol. 1, p. 381) it is stated that discrepancies up to 90° are observed. Again, in an article by Dr. Bellini in the *Electrician* (1921, vol. 86, p. 220) it is stated that the errors may vary as much as 50°, 60° or even 90°. Most of the writers at this period sought to attribute the varying accuracy of direction-finding to the uneven reflecting surface of the "Heaviside layer." Even here one is again in difficulty because in the *Electrician* (1922, vol. 89, p. 148) there is an article which goes to suggest that the Heaviside layer does not exist, but to-night one speaker has given us a most interesting exposition of the action of the Heaviside layer and why it causes direction-finding to be more accurate on spark than on continuous-wave stations, and a further speaker has revealed that there is a difference of opinion as to which system gives the most accurate determination of direction. Again, the paper and the discussion thereon have shown a marked difference of opinion as to whether the locating of ships at sea should be by means of direction-finding equipment on board the ship or on the shore. From what I have said it will be apparent that there is controversy on so many phases of the subject as in my opinion to justify the belief that it is too early to say that any system of direction-finding for the purposes of navigation has arrived at the stage where it may be regarded as being sufficiently reliable.

Major H. P. T. Lefroy: It will be a great disadvantage if continuous-wave transmission must finally be accepted as unsuitable to employ for signals whose bearing is to be taken. The difference between the reception of this and other systems lies in the use normally of a local oscillator, which is, I believe, frequently the cause of the error in the apparent bearing. I am inclined to think that the "ticker" method, properly applied, would be more suitable than a local oscillator, in that it would make for a greater degree of accuracy in practical work when taking continuous-wave bearings, though the strength of signals received would be less.

Major A. G. Lee: I am in fair agreement with the author in regard to the figures which he puts forward in connection with radio beacons, but in view of what we have heard from Mr. Keen on the one hand and from Dr. Smith-Rose on the other, it seems to me that the suggestion that the spark system is definitely better than the continuous-wave system is by no means fully proved, and before we as a country commit ourselves to radio beacon stations on the spark system (which will be without doubt a nuisance to broadcasting, amongst other interests) this question of the relative advantages of the two systems should be more thoroughly thrashed out than it has been up to the present time. The Radio Research Board have done a considerable amount of work on this subject, and are of opinion that the continuous-wave system is as good as the spark system. It would be very useful if the Marine Wireless Companies interested in the subject could take advantage of the information accumulated by the Radio Research Board and could combine with that Board with a view to arriving at some definite conclusion.

Mr. E. H. Shaughnessy: The author says that he is dealing with bearings taken from the ship. That is very interesting, because the area that he shows in one instance to my knowledge corresponds almost exactly to what we know to be the correct range from the direction-finding station. There is another point on which I think we should be quite clear. I was particularly impressed with the percentage of accurate bearings given in the table on page 549. I should like to know, however, whether this 91 or 95 per cent of accurate bearings are the bearings obtained within the known "safe" area of taking bearings. If that is the case, then we have to realize that it puts a very strict limitation on the utility of direction-finding. With the compass we do not have to mark off areas all over the globe in which there are very limited angles only within which the reading can be relied upon. We know that if there is a station well inland, and the directions are taken from an angle of almost 90° with the coast line, we are likely to get reasonably consistent results perhaps 95 or 98 per cent correct within 2°. But what happens when we work along the coast line? There is the danger area, so that in talking of direction-finding being 98 per cent correct within 2°, and almost as accurate as the compass, it is necessary to place a limitation on such statements, which limitation we do not have to place on the ordinary use of the compass. I do not quite understand the author's suggestion with regard to a new Department of Direction-Finding Control. He means, I suppose, some department for examining all direction-finding installations that are put on ships. I do not quite know what control any new department or existing department could exercise in any such respect.

Commander J. A. Slee (*in reply*): In reply to Mr. Bainbridge-Bell, so far as experience of the Bellini-Tosi system goes, a change of calibration error due to change of draught has only been reported once and an investigation of this case showed that the system was improperly earthed. When this was rectified the change disappeared, and it can be stated that no change of calibration is found necessary with changes of draught.

With reference to the bad-bearing areas, it is highly desirable that some official department should deal with this matter, though it appears that the whole subject is as yet too young and the number of ships fitted too small to expect any Government Department to undertake the work at this stage. The arcs of bad bearing shown on the lantern slides have been completed with a view to guiding the seaman and to warn him against relying on bearings taken from positions where they are likely to be indifferent. They do not represent a scientific examination of the exact boundary line. Experience shows that within distances of great importance for navigation—that is to say, up to 100 miles—the straight lines shown on the slides give a very fairly accurate representation of the facts.

Referring to Prof. Fortescue's remarks, the width of the silent arc is of no real importance provided that the cut-off is sharp so that the vanishing points can be determined with certainty. Provided that these points are clearly fixed, obviously it cannot matter whether they are 60° or 60 minutes apart. Bearings only become doubtful when the position of the vanishing point becomes difficult to determine.

It is pointed out that when a direction-finder is mounted on board an iron ship its environment is such as to make possible a large number of errors which are probably due to changes in conductivity, etc., in the whole structure of the vessel, and the object of the paper has been to explain how these difficulties have been overcome and what results can be obtained under these conditions. The methods now in use have been selected as the result of a great many trials.

Many of the points raised by Dr. Smith-Rose are dealt with in my reply to the remarks of Prof. Fortescue. Dr. Smith-Rose speaks of loops as small as 70 sq. ft. in area. In the paper it is stated that the size of loops ranges up to about 400 sq. ft.; loops as small as 70 sq. ft. are only used in special cases in very small vessels such as trawlers. Furthermore, it is stated in the paper that small loops are unsatisfactory in large vessels. The common size of loop is about 240 sq. ft. The lack-of-symmetry error can be and, in some cases, is reduced by the use of screens, but such a construction is in many cases perfectly impossible under merchant-ship conditions. This paper does not profess to be a comparison between the Bellini-Tosi system of direction-finding and systems employing moving frames, and I do not think that any useful purpose will be served by entering into such a comparison.

There are about 120 British merchant ships fitted with the Bellini-Tosi system of direction-finding, and the reports from 99 of these are constantly under review. From these reports the figures quoted have been obtained and there is no reason to suppose that the results obtained in the other ships are any worse. The total number of American merchant ships fitted with direction-finders is 41 and, although definite reports as to their performances are not available, it is believed that the degree of accuracy which they obtain is lower than that quoted in the paper. The distribution of direction-finders in the merchant vessels of the chief nations is approximately as shown in the following table. No

figures are to hand for German, Swedish or Japanese vessels.

	Bellini-Tosi	Frame
Great Britain	121	?
United States	—	41
Germany	?	?
Sweden	?	?
Japan	?	?
Norway	9	—
Belgium	3	—
Spain	22	—
Portugal	1	—
Italy	52	—
France	—	32
Holland	6	—

With regard to the latter part of Dr. Smith-Rose's remarks, the small amount of experience available on the subject indicates that from a fixed position the error due to "land effect" is constant, but the matter has not been explored as it is clear that the error varies considerably with slight alterations of position. It is certain that a badly arranged local oscillator will cause errors in bearings, but it is doubtful if this cause will account for variations in a bearing which ought to remain constant. No difficulty has been found in arranging a local oscillator so that it makes no difference at all (except breaking up the note) to the steadiness or accuracy of spark bearings.

With reference to Major Binyon's remarks on the subject of the position of direction-finders in ships, it may be of interest to know that so far only three Bellini-Tosi direction-finders have been erected (at the request of the shipowners) for working on the bridge. One of these has been removed to the wireless office, also at the request of the shipowners.

In reply to Mr. Bennett, it does not seem really necessary to record on sketches the error to which he alludes, as no sea-going ship is ever likely to get close enough to a wireless station for this error to be noticeable.

In reply to Mr. Nash, it appears that the state of affairs to which he refers can be cleared up as follows:—Results which are reliable from a navigational point of view can be obtained by the Bellini-Tosi direction-finders from spark transmitters. This does not state that reliable bearings cannot be obtained from other types of transmitters. A great deal of past experience shows that bearings taken at night by direction-finders of continuous-wave transmitters are not reliable. On the other hand Dr. Smith-Rose states that reliable bearings can be obtained under such conditions.

There is no doubt that it would be to the general advantage if further experiments were to show that reliable navigational bearings can be obtained from continuous-wave transmitters, and experiments to settle whether the continuous-wave system is or is not a suitable form of transmission for navigational purposes are now in progress, bearing in mind the adverse conditions under which a direction-finder is used on board ship. The use of the interrupted continuous-wave system may prove to be the best solution.

With reference to the remarks of Major Lefroy, it is possible that the use of a chopper may be found advantageous.

In reply to Mr. Shaughnessy, the "arcs of good bearing" indicated on the lantern slides apply only to bearings taken by ships of the land station. The last two columns of the table have been made up after the bearings outside the "good bearing" areas had been rejected. Previous to May 1923 all bearings were lumped together.

There are a few patches of fairly shoal water where the sea bed appears to be of an ironstone nature, in which the compass is likely to become inaccurate, but this comparison between the reliability of the compass and that of a direction-finder does not seem to be quite fair. It is more just to lay the blame for "arcs of bad bearing" on the positions of the coast stations, and to mark the "arc of good bearings" in the same way that all lighthouses erected on land have a definite arc of visibility, outside of which they cannot be used, indicated on the chart. Arc of bad bearings are entirely a matter of the intervention of land between the ship and the transmitting station; they have nothing to do with the general conditions of the locality, such as the nature of the sea bed.

The author does not suggest a new Department of Direction-Finding Control. He only expresses the hope that in the future, when a large number of vessels are fitted, some Government Department will undertake the duty of publishing official documents indicating "arcs of good and bad bearings."

INSTITUTION NOTES.

Council's Nominations for Election to the Council.

The following have been nominated by the Council for the vacancies which will occur in the offices of President, Vice-Presidents, Honorary Treasurer, and Ordinary Members of Council on the 30th September next:

President. *(One Vacancy.)*

W. B. Woodhouse.

Vice-Presidents. *(Two Vacancies.)*

S. Evershed. A. Page.

Honorary Treasurer. *(One Vacancy.)*

P. D. Tuckett.

Ordinary Members of Council.

Members. *(Four Vacancies.)*

W. E. Highfield. B. Longbottom.
H. W. Jones. E. H. Shaughnessy, O.B.E.

Associate. *(One Vacancy.)*

The Viscount Falmouth.

Informal Meetings.

The Informal Meetings Committee will consider, in the course of the next three months, the programme for the session 1924–25, and will be glad if members will indicate to the Secretary subjects which they suggest for discussion.

Members willing to open discussions are invited to submit, for consideration by the Committee, the subjects on which they wish to speak; a written paper is not necessary.

Associate Membership Examination Results: April 1924.

Passed.

Ashford, D. G. (Bristol).
Baker, E. W. (London).
Bannatyne, A.M.(London).
Baxter, J.MacG.(Croydon).
Bennett, E. H. (Bromley, Kent).
Bent, F. (Bolton).
Cantelo, H. R. (Southampton).
Cawson, W. F. (Hull).
Chase, J. J. (Norwich).
Chorlton, H. C. (Newcastle-on-Tyne).
Dennis, W. E. (Hull).
Drape, S. (Heaton).
[illegible]unbar, L. (London).
[illegible]n, A. (Bangor, Ireland).
Esmond, L. P. (Chelmsford).
Frost, A. H. (London).
Grant, D. F. (Gravesend).
Hargreaves, T. (Rochdale).
Hitt, D. G. (Plymouth).
Hodges, L.A.(Birmingham).
Hollis, G. R. (Manchester).
Hollyman, R. H. (London).
Ibeson, W. (Huddersfield).
Jones, R. C. (Pontypridd).
Leslie, G. H. (Sandhurst).
Lewis, W. K. (London).
Metcalf, H. E. L. (Hertford).
Nisbet, R. H. (Longfield).
Patterson, J. H. (Solihull).
Pearce, R. (London).

Associate Membership Examination Results: April 1924—*continued.*

Passed.

Pinkney, W. H. (Stafford).
Poolman, C. G. N. (Preston).
Powell, E. B. S. (London).
Rann, J. S. (London).
Roddam, G. (Rutherglen, Glasgow).
Savage, A. N. (Newport, Mon.).
Steel, R. W. (Stoke-on-Trent).
Thompson, S. W. (Hull).
Tobin, E. (London).
Topley, H. (Mansfield).
Westell, E. P. L. (London).
Withington, R. L. (Guildford).

Passed Part I only.

Warder, L. I. (Sandown, Isle of Wight).

Passed Part II only.

Lieberg, O. S. W. (London).
Miles, T. S. (Norwich).
Moore, R. E. (Doncaster).
Rawlings, B. C. (Bilbao, Spain).
Wood, A. G. (London).

Further results relating to candidates who sat for the Examination abroad will be published later.

Officers of the Corps of Royal Engineers.

(School of Military Engineering, Chatham.)

Passed.

Bainbridge, 2nd Lieut. H.
Baines-Hewitt, 2nd Lieut. F. B.
Bright, 2nd Lieut. C.P.C.S.
Cardale, 2nd Lieut. W. J.
Clarke, 2nd Lieut. E. W. H.
Cotton, 2nd Lieut. B. H. C.
Croghan, 2nd Lieut. E.
Croucher, 2nd Lieut. M. J.
Easton, 2nd Lieut. P. A.
Egerton, 2nd Lieut. R. C.
Empson, 2nd Lieut. G. L.
Fayle, 2nd Lieut. L. R. E.
Gardiner, Lieut. R.
Grattan, 2nd Lieut. H.
Grose, 2nd Lieut. D. C. E.
Grylls, 2nd Lieut. J. A. B.
Heard, 2nd Lieut. L. F.
Hume, 2nd Lieut. P. W. G.
James, 2nd Lieut. J. E. L.
Kirkbridge, 2nd Lieut. W.
Knott, 2nd Lieut. A. J.
Lloyd, 2nd Lieut. T. I.
Loch, 2nd Lieut. I. G.
Macdonald, 2nd Lieut. H.A.
Murray, Lieut. D. M. J.
Pegler, 2nd Lieut. C. A. W.
Preston, 2nd Lieut. G. W.
Reed, 2nd Lieut. W. P.
Rees, 2nd Lieut. J. L.
Ricketts, 2nd Lieut. L.T.G.
Stenhouse, 2nd Lieut. E. E.
Sugden, 2nd Lieut. C. S.
Thomas, 2nd Lieut. L. G.
Thompson, Lieut. J. H. C.
Walker, 2nd Lieut. R. J.
Walkey, 2nd Lieut. J. C.
Watkinson, Lieut. G. L.
Wilson, 2nd Lieut. I. H. R.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 April–24 May, 1924:—

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THE DESIGN OF APPARATUS FOR THE PROTECTION OF ALTERNATING-CURRENT CIRCUITS.

By A. S. FITZGERALD, Associate Member.

(*Paper first received* 14*th September*, 1923, *and in final form* 10*th January*, 1924; *read before* THE INSTITUTION 28*th February*, *before the* NORTH-EASTERN CENTRE 25*th February*, *before the* NORTH MIDLAND CENTRE 26*th February*, *before the* NORTH-WESTERN CENTRE 4*th March*, *before the* SCOTTISH CENTRE 11*th March*, *before the* SHEFFIELD SUB-CENTRE 19*th March*, *before the* WESTERN CENTRE 7*th April*, *and before the* SOUTH MIDLAND CENTRE 30*th April*, 1924.)

SUMMARY.

The paper deals with differential protective systems, particularly those suitable for use where there is a neutral earthing resistance.

The operating conditions, and their influence on methods of design and construction, are discussed, and improved means of practically applying the various protective circuits are described.

The superiority of biased systems, in principle, is accepted as having been established, but the objections to a more complicated relay are recognized. The author advocates the use of simple relays only, in order to restrict to a minimum the employment of moving parts associated with small amounts of power.

The necessary functions peculiar to biased and certain other protective systems have led to the use of balanced beam, dynamometer, and other special forms of relay. The paper describes how these features may be achieved with a simple relay and a static device called a "biasing transformer."

Current transformers and simple types of relay are briefly dealt with, and a further static device called a "phantom auxiliary switch" is described.

The application of the foregoing apparatus to actual protective circuits is described in the second portion of the paper, and attention is drawn to the advantages of dealing with earth faults and line faults independently.

TABLE OF CONTENTS.

INTRODUCTION.

Several papers dealing with this subject have been read and discussed before the Institution, and much helpful expression of opinion and useful experience have been made public.

In the present paper the author describes certain methods and devices whereby the ideals and objects aimed at and expressed may more nearly be approached.

No new principles or fundamentally novel circuits will be found in the paper, but the author endeavours to indicate how existing methods may be made simpler and more reliable by the use of apparatus operating on well-known principles and presenting no new features of construction, but which has not in the past been associated with protective gear.

It is proposed to restrict the paper to a description of differential systems of protection only, and to the class of protective gear operative on flow of current, rather than to arrangements of a preventive nature.

The systems described will be those considered specially suitable for supply systems operating with a neutral earthing resistance.

General agreement with the principle of instantaneously clearing earth faults of reasonably small value is assumed, as is also the necessity for protective relays being of the simplest design as well as of robust construction.

Section 1.

GENERAL FEATURES OF DESIGN.

The nature of the requirements associated with protective gear presents more stringent conditions to be met, and demands greater precision and reliability of operation, than is the case in almost any other class of electrical apparatus.

The principal features of difference between the more

common forms of electrical circuits, instruments, etc., and the devices comprising a protective system, may be considered under the following headings :—

Reliability.—Occasional failure, whilst admittedly undesirable, may be commercially permissible, in most ordinary classes of apparatus, to an extent depending on considerations of maintenance.

Moreover, such failures will be readily brought to light in the ordinary course of duty.

The primary function of protective gear is to function with absolute certainty on the occurrence of trouble, and any shortcomings in this connection may not be discovered until an actual fault has occurred.

Conditions of service.—The requirement of reliability, to the maximum extent commercially obtainable, is common to all devices created by the engineer, but only in a very limited range of apparatus, which includes protective gear, is it an essential feature of the working conditions that the operation shall only be effected on very infrequent occasions.

In the general case it must be admitted that constant use is one of the circumstances whereby the operating mechanism is maintained in a state of efficiency.

Range of operation.—Neither machines, instruments, nor control circuits are expected in the ordinary way to perform the function for which they are designed, over a range exceeding to any great extent a ratio of 10 to 1, either of current or voltage.

A protective system, on the other hand, whose function is to discriminate between the flow of current due to local or remote faults, must carry out this operation with precision when subjected to currents the magnitude of which may vary from that of an earth fault current, of the order of 50 amperes, to that associated with the short-circuit current which may flow due to a breakdown between lines on a large network. Such fault currents have been known to exceed 20 000 amperes.

Responsibility.—In a protective circuit will be found certain items of apparatus consisting of current transformers, relays, etc., variously arranged and connected, and involving wiring and contacts, the whole, as a rule, being energized to the extent of a few volt-amperes and being correspondingly proportioned.

Directly dependent, however, on the small operating forces and light moving parts necessarily associated with the limited energy available, there may be not only generating plant, mains, etc., representing an appreciable percentage of the total capital involved, but also, in an industrial area, means of production of which the output may be computed in hundreds of pounds per minute.

It will be seen, therefore, that such electrical apparatus, which is in itself trivial and insignificant when compared with the majority of the machines or devices met with in an electrical power station, is rarely so applied that unsatisfactory performance of the gear itself is likely to give rise to results more unfortunate financially or of greater extent.

Limitations of protective circuits.—It would seem that a very good case might be made out for a direction of development closely following that which has proved successful when applied to control devices and circuits. Present practice in this sphere favours the use of mechanical principles and ample operating forces rather than numerous electrical components, especially those involving small contacts. Methods of discrimination, therefore, which involve selective contacts in series, cannot be considered as a line of development likely to lead to the standard of reliability essential to the success of a protective system.

Similarly, every effort should be made to provide operating forces as large as possible, but it is precisely in regard to this feature that the protective circuit is at a disadvantage.

Much better results will attend the employment of transformers capable of increased output, rather than endeavour directed to the design of sensitive relays, but there are definite limits to such a line of development.

Owing to the desirability of clearing an earth fault at an early stage in its development, the energy available for operating relays under such conditions can scarcely exceed a few volt-amperes.

For this reason, therefore, the above argument in favour of employing mechanical principles does not seem equally applicable to protective apparatus.

Stability.—Immunity from incorrect operation due to " through " currents is of equal importance to certainty of operation on the occurrence of a fault. It is notably in this respect that existing methods of protection have not always been found adequate.

The magnitude of the disturbances which may be met with on large systems is now realized to exceed the range within which uniform performance of ordinary current transformers may be relied upon.

Only where air-gap transformers are used can balance be properly obtained under short-circuit conditions, but this practice leads to the necessity for very sensitive relays if limited earth faults are to be dealt with.

It is to be noted that these difficulties are definitely associated with the employment of a system depending for its operation on the direct difference between the effects concerned. Much more satisfactory results have attended the efforts which have been made to arrive at a solution along other lines.

Biased systems.—This reference is intended to cover those systems of protection in which the value of the difference current necessary to effect operation of the relays is not a fixed quantity as in the case of a relay connected in a differential circuit and having a given current setting, but one in which the amount of the difference current required is augmented as the load current, transmitted by the circuit protected, is increased. In order to give effect to this principle, existing methods have employed what is referred to as a biased relay, this term denoting a relay having a variable electrical bias in addition to, and distinct from, the constant mechanical bias due to gravity, a spring, or other controlling force.

The construction of a relay of this type will necessarily be less simple than that of a plain relay having but one electromagnetic element. It is well known that difficulty is met with in designing biased relays in forms sufficiently sensitive to be operated by the limited energy available, on account of the considerable forces which they must withstand without operating.

A perusal of the published expressions with regard to the principle involved, indicates clearly that the principle of biasing is accorded general support. The employment of forms of relay departing from the simplicity of the single element, however, is deprecated and much difference of opinion exists as to whether this objection is outweighed by the advantages associated with the use of biased relays. The author, however, feels justified in assuming general agreement with the biasing principle as applied to a protective circuit, provided that the objections above referred to are avoided and the advantages retained.

Static Method of Providing Bias.

It is required, therefore, to provide a means of restraining a relay from operation, as well as actuating it, without the necessity of introducing into the relay additional forces and components.

In making comparison between the relays incidental to biased systems of protection and arrangements which do not present this feature, the protection of a single circuit was implied. Where the protection of parallel circuits as such is concerned, however, the employment of balanced-beam or similar forms of relay is usual, whether the fault setting varies with the through current or not.

A further field of application is therefore seen to present itself to a method of carrying into effect, by more simple means, the function hitherto performed by differential or biased relays.

A very simple method of restraining the relay from operation is provided if, instead of introducing additional forces in opposition to the operating effect, a reduction in the magnitude of the latter be brought about.

It would seem, therefore, that there is required some form of intermediate device connecting the operating effect with the relay and capable of transmitting to the latter such proportion of the available energy as may be appropriate to the circumstances under which the apparatus is functioning.

To meet this requirement the author has employed a device which, whilst its use in connection with certain special systems of control is on record, has not, to his knowledge, undergone extensive development, nor has it hitherto entered the sphere of practical engineering. In its simplest form it consists of a transformer of special design and possessing the following novel features. Whilst it has, in common with other forms of transformer, a secondary winding and a primary or operating winding, it is provided with a further winding, described as a restraining winding, in order to indicate its function. This latter winding is not inductively related to the operating or secondary windings, but it excites a magnetic circuit a portion of which is common to that with which the other windings are linked.

Such an arrangement might consist of a pair of ring cores as in Fig. 1 (*a*), each provided with similar operating and secondary windings connected in series; a third coil present on each core but in one case reversed in relation to the other windings will, if excited, have the following effect. Such E.M.F.'s as may be induced in each secondary by this third coil will not appear in the complete secondary circuit as they will be in opposition; nevertheless the magnetic circuits of both transformers will be excited. If such proportions be chosen that currents flowing in the restraining winding give rise to saturation of the iron, this will clearly affect the secondary current corresponding to any given operating excitation, since the secondary ampere-turns will roughly be equal to the difference between the primary and magnetizing

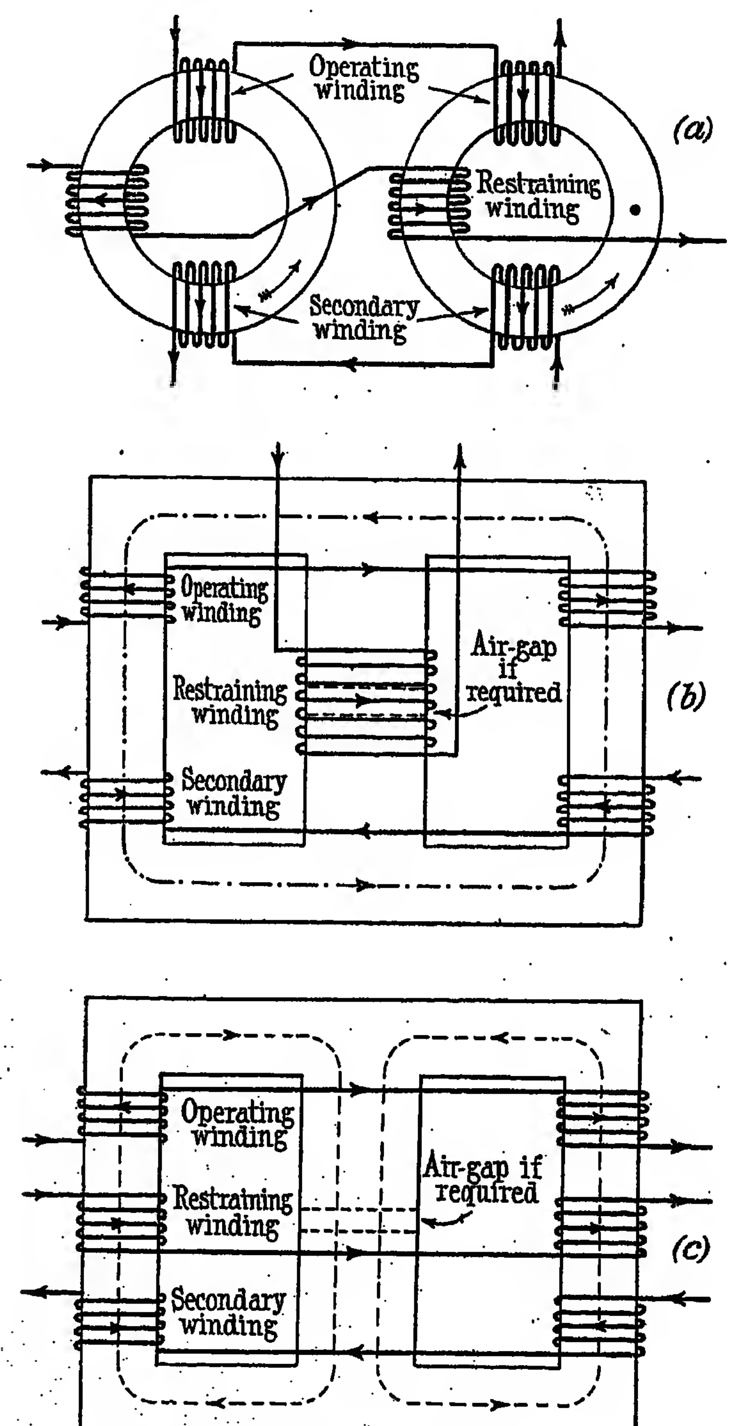

Fig. 1.—Forms of biasing transformer.

ampere-turns. Excitation of the restraining winding is capable of increasing the reluctance of the magnetic circuit to such an extent as will necessitate a very much greater operating current in order to deliver the required secondary energy. If, therefore, the operating winding be connected in place of the protective relay, this being connected to the secondary, the desired effect is obtained.

Whilst the above scheme is one of the most efficient

forms of restraining winding, the author employs a somewhat different method presenting peculiar advantages. In lieu of the pair of cores described, a single core, having three limbs, of the form shown in Fig. 1 (*b*), is used. This shape enables two magnetic circuits to exist in the one core, each of which has a common portion as specified, and coils may be arranged in various ways to have inductive relation with either of the magnetic circuits.

Windings appropriate to the excitation of one or other of these magnetic circuits may, however, themselves be mutually non-inductive. The restraining winding, for instance, may consist of a single coil situated on the central limb, as in Fig. 1 (*b*).

Divided operating and secondary windings will then be employed, consisting of two coils having equal numbers of turns, each being on one of the external legs of the core. This sets up a flux as indicated by the chain-dotted lines. A more efficient restraint, however, is given if divided restraining windings are employed,

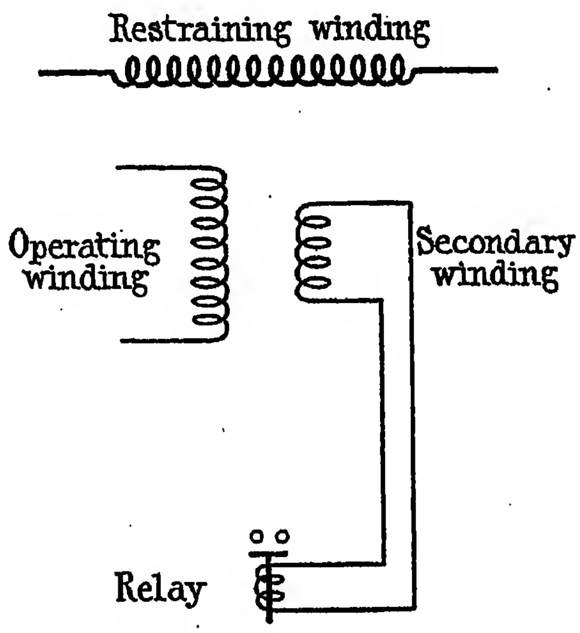

FIG. 2.—Method of indicating windings of biasing transformer.

as shown in Fig. 1 (*c*). In either case the restraining winding gives rise to a saturating flux passing through the centre, as shown by the dotted lines in Fig. 1 (*c*).

This form of construction is obviously superior to the ring arrangement, since former-wound coils may be used in which laminations, conventionally jointed, may be assembled. It will be seen that the core is laminated in one plane only. A further advantage, however, is that an air-gap may be provided in the restraining magnetic circuit without reducing the unrestrained permeability of that associated with the other windings. This enables very useful restraining characteristics to be achieved, as will be more readily comprehended in relation to the various methods of applying this device to protective circuits. These characteristics will be more fully explained later in the paper.

It might perhaps be thought that the employment of this device would be inclined to lead to internal balancing difficulties peculiar to its construction. It is to be pointed out, however, that it is clearly less difficult to procure uniformity between two halves of the same set of laminations than where separate cores are involved. Even where, due to careless assembly of the core, a lack of symmetry is produced, the author's experience is that unless cores of a much larger size than those which he employs are used, the out-of-balance current in the relay when the heaviest restraining current is flowing cannot be detected by any instrument of such range as might be used to indicate the tripping current of the relay.

In order to carry out the various requirements in connection with the different schemes to be considered, it is often necessary to employ more than one transformer element, and in such cases these will be connected in cascade, i.e. the secondary winding of one transformer will be connected to the operating winding of another, and so forth, the relay being excited by the final secondary.

In order to avoid complication in diagrams of protective circuits of this nature, a simple form of representation of the various windings, as shown in Fig. 2, has been adopted in all the diagrams which follow. In every case, therefore, the restraining winding will

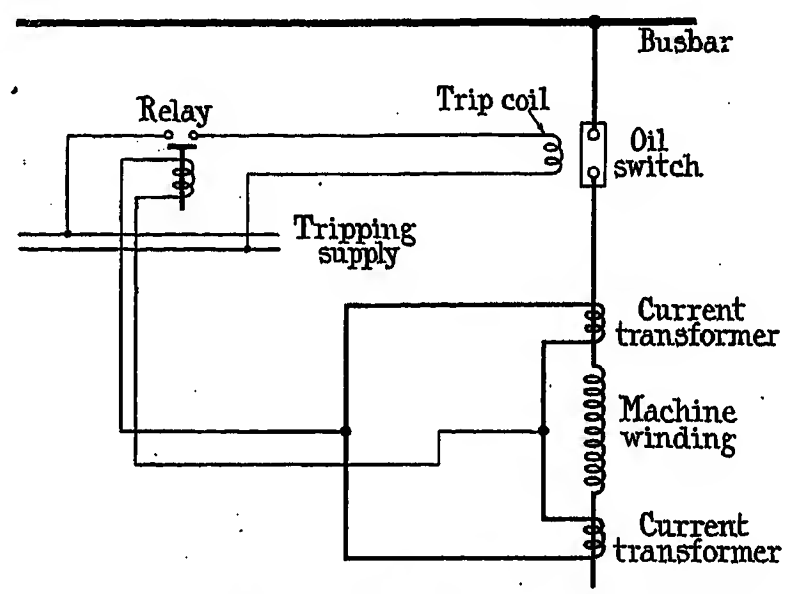

FIG. 3.—Simple circulating-current protective circuit.

be shown horizontally and the operating and secondary windings the longer and shorter respectively of the two vertical indications.

A combination, therefore, of biasing transformers and simple electromagnetic relays may discharge the functions usually performed by balanced-beam relays, differential induction relays, or dynamometer relays in applications of the foregoing to balanced-current protection, reverse-power apparatus, and differential forms of the latter.

The principal functions of the biasing transformers applied to systems of protection are as follows:—

(1) Overload restraint.
(2) Discriminating restraint.
(3) Directional discrimination.
(4) Auxiliary restraint.

(1) *Overload restraint.*—In order to apply the feature of overload restraint the operating winding will be connected so as to receive the difference current, and the restraining winding will be connected in a suitable portion of the protective secondary circuit carrying current proportional to the load on the unit protected.

In the majority of differential protective circuits this will be known as the "circulating current" circuit.

Fig. 3 shows what is probably the simplest form of protective circuit, viz. the protection of a single winding or conductor on the circulating-current system. It will be seen that the two current transformers are connected so that current normally circulates between them when their primaries are carrying equivalent currents, but that in the event of a fault on the winding protected—to the effect that the entering and leaving currents are no longer of equal magnitude—there will appear a difference current in the relay, this being connected between equipotential points on the circulating-current circuit.

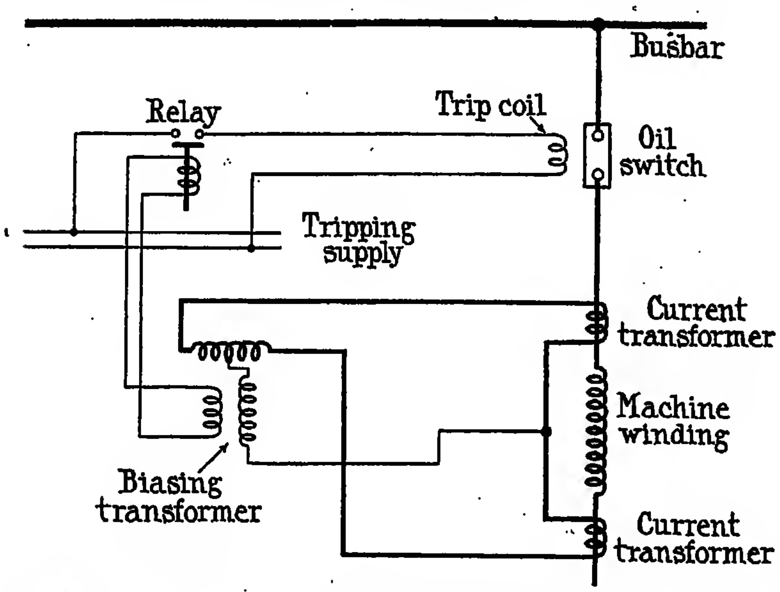

FIG. 4.—Application of biasing transformer to circulating-current circuit.

This relay will be of simple design, having no differential feature. It will therefore operate at a given value of difference or fault current irrespective of the "through currents" which may traverse the protected circuit. This arrangement is well known and has been widely used. It has given entire satisfaction within its sphere of utility, which is limited to cases where no great sensitivity is aimed at and where it is possible to provide accurate balance between the current transformers, or where, alternatively, the protected plant will not be subjected to the effects of heavy external faults.

There is scope for improvement in performance in many instances and, by the employment of the biasing transformer, this may be achieved with freedom from additional complication.

An equivalent protective circuit is outlined in Fig. 4. A relay similar to that embodied in the scheme shown in Fig. 3 may be utilized in this circuit. In accordance with the principles indicated above, the operating winding of the biasing transformer is connected in Fig. 4 where the relay was shown in Fig. 3. The relay is excited from the biasing transformer secondary, whilst the restraining winding is included in the circulating-current connections. In order that the operating winding shall continue to receive the true difference current, the restraining winding must clearly be symmetrically disposed with regard to it, and accordingly one end of the former will be taken to a mid-point on the restraining winding. This modification endows the protective circuit with the characteristics shown in Fig. 5, which gives the relation between the current in the restraining winding (that is to say, the transmitted load or "through current"), and the operating excitation. In other words it shows the difference or fault current necessary to cause the relay to trip.

Fig. 5 shows the magnitude of restraint that can be achieved under these conditions. The actual value attained will depend, of course, on the number of turns on the restraining coil, and a restraining action of the full extent indicated may not, in every instance, be necessary or desirable.

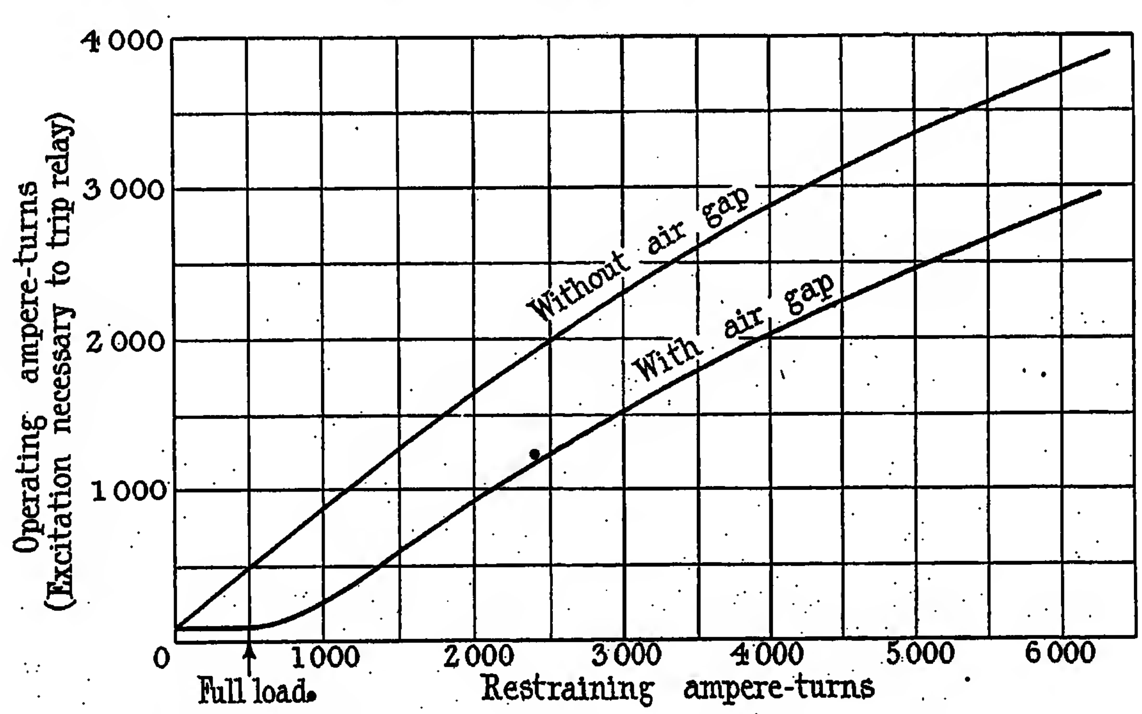

FIG. 5.—Characteristic curve of biasing transformer; overload restraint.

The use of the biasing transformer, however, renders possible the provision of a further advantageous feature not usually inherent in systems employing biased relays.

In any scheme in which restraint is derived from current proportional to the transmitted load, there is likely to be present at normal load a corresponding fraction of the restraint provided under overload conditions, and, unless the latter be of moderate extent only, the full-load sensitivity will be appreciably less than the maximum of which the protective circuit is capable.

In this connection there will be seen the utility of the central air-gap to which reference has previously been made. Under normal circumstances when the transmitted load and, accordingly, the restraining current, is of no very great magnitude, the presence of the air-gap will materially reduce the restraining effect, causing as it does a very marked increase in the reluctance of the magnetic circuit carrying the restraining flux. When, however, due to remote faults or overloads, the restraining excitation is of the order of magnitude capable of saturating the core of the biasing transformer, the effect of the air-gap will be very much less, in fact almost inappreciable, since the permeability of the core itself in this state will more nearly approximate to that of an air path. The upper curve in Fig. 5 indicates the characteristic of a biasing transformer in which the central member is not furnished with an air-gap, whilst the lower curve corresponds to the provision of a suitably designed magnetic circuit in which one is present.

Thus it is possible to arrange that the inherent sensitivity of the protective circuit shall not be impaired by the presence of the restraining effect until the transmitted load or fault current considerably exceeds the rated load of the unit protected. It is not until currents of this order of magnitude are attained that the difficulties associated with current-transformer balance, etc., which postulate the provision of a biased protective system, become in evidence.

On the occurrence of a fault within the area embraced by the protective circuit, however, the difference current flowing in the operating winding is able, under conditions of maximum efficiency, to effect the isolation of the defective plant through the actuation of the relay.

Consideration of another aspect of the design of protective apparatus will disclose an additional benefit incidental to the use of this device. The provision of very sensitive fault settings has been restricted in the past by considerations of immunity from incorrect operation, having regard to the question of balance, and accordingly there has been no extensive use of relays capable of operating at small values of energy except where, due to the type of protective transformer provided, the available volt-amperes are of an extremely low order, in which case the use of such relays has not given rise to notably advantageous sensitivity.

The extreme range of current values over which it is necessary for protective gear to operate has already been indicated, and it will be immediately apparent that improvement in the sensitivity of a protective system has the effect of extending the limits within which accurate and correct performance must be achieved.

Reduction in the fault setting may be arrived at in two ways. First, relays of a highly sensitive design may be used; and secondly, a more efficient protective circuit may be evolved, i.e. an arrangement of transformers and connections capable of delivering to the protective relays, for any given fault effect, an increased amount of energy.

The immediate effect of the latter method of improvement will be to give rise to mechanical forces of augmented magnitude exerted on the movable portions of the relays when a heavy fault occurs. If at the same time additional improvement be sought in the direction of more sensitive relays, it is evident that difficulty will be met with, the forces accompanying a short-circuit on the plant protected becoming of destructive magnitude if this line of attack be indefinitely pursued.

As the biasing transformer will have a magnetic circuit of restricted cross-section, this will become saturated by operating current alone when it exceeds, to any great extent, the value necessary to effect tripping of the relay, even though the restraining winding is not energized. The secondary output will therefore be correspondingly limited, as will also the maximum force which may be developed in any relay operated by the biasing transformer, no matter to what magnitude the fault current may increase.

In applying the biasing transformer to differential circuits with a view to the provision of overload restraint, one essential characteristic of this class of apparatus must be borne in mind, viz. the relation which will exist between the extent of the restraining effect and the phase displacement of the restraining current with regard to that flowing in the operating winding. As may be anticipated, the restraint will be a maximum when the phase angle is zero and will be a minimum when the two effects are in quadrature. It is to be noted, however, that the restraining action is by no means non-existent even in the latter case. In the case of overload restraint it will further be obvious that the actual value of the restraint is not essentially of any great importance provided that it is sufficient for its purpose under the least favourable circumstances, and that when operating and restraining currents are coincident in phase the decrease in sensitivity is not appreciable under conditions of normal loading.

No difficulty has been encountered in meeting these requirements, and the author has carried out a very large number of tests of an exhaustive nature in this connection, "turn errors" and other discrepancies having been introduced into the current transformers employed. As a result it has been demonstrated that, in the matter of current-transformer balance, ample restraint may be applied without more than a small fraction of the maximum possible effect being brought into use. In one instance samples of a proprietary steel from entirely different mills were supplied by the manufacturers. Transformers built from different batches were tested together in a simple protective circuit and it was found that the relay tripped with through currents of less than 10 000 amperes. When, however a biasing transformer was employed, a low-impedance instrument connected in series with the relay and giving a half-scale deflection with the current at which the relay was set to trip, gave no perceptible reading when the maximum obtainable current (considerably in excess of 10 000 amperes) was applied.

There will, of course, be a certain loss of secondary tripping current due to the additional transformation, but the sensitivity is unimpaired if the relay setting be reduced by 20 per cent. In unbiased systems, however, the question of stability will determine the setting of the relay rather than the question of the minimum volt-amperes at which the relay is capable of operating. The employment of the biasing transformer, in fact, renders possible the use of a very much more sensitive relay should this be desired.

(2) *Discriminating restraint.*—In the foregoing it has been shown how a biasing transformer may advantageously be applied to a simple differential protective circuit, i.e. one in which it is desired to effect operation of a single relay on the occurrence of a difference between two currents which are normally equal.

In many well-known systems, notably those concerned with the protection of parallel circuits, a more extended function is required. In such instances the protective apparatus will, as before, be called upon to compare normally equivalent currents, and to operate in the event of inequality. There will, however, be more than one relay, each associated with a particular circuit, and it will be necessary to give rise to tripping of one particular relay, usually that carrying the greatest current. It will be of corresponding importance in such applications that relays other than the one specified shall be immune from operation.

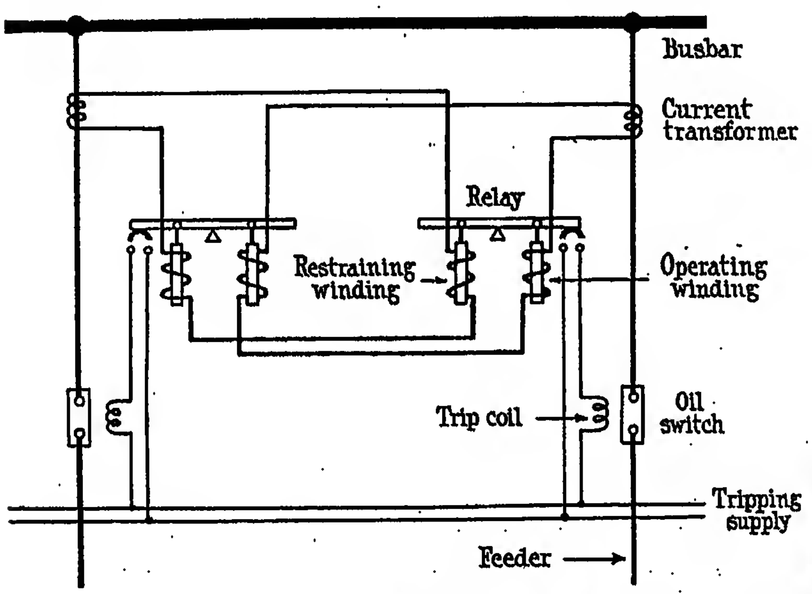

Fig. 6.—Discriminating balanced-beam relays.

It is apparent, therefore, that systems of this nature are necessarily those referred to previously in the paper, when it was pointed out that the employment of balanced, biased or differential relays was inevitable in circuits of this form.

The simplest case is that of direct balance between two feeders, when, as in Fig. 6, two simple mechanically balanced relays of the beam type might be used. Each of these relays is arranged, as shown, to trip out the line from which it derives the current exciting the coil which tends to close the contacts. The restraining coils are each connected in series with the operating coil of the opposite relay and current transformer. Assuming equal turn ratios, etc., both relays will be balanced when the load or other currents are carried to the same extent by both lines. If one of the feeders carries an excessive current, due perhaps to a fault, the corresponding relay will be subjected to an augmented force, in excess of its restraining effort, tending to actuate it. This relay will accordingly operate, whereas on the other there will be increased restraint and the sound line will remain in service.

Fig. 7 shows an analogous scheme in which ordinary relays and biasing transformers are substituted for the balanced relays, no other change being made in the connections. With such an arrangement a similar performance may be obtained. This will be more clearly understood by reference to further characteristic curves of the biasing transformer. As shown by the curve in Fig. 5, referring to a biasing transformer having a closed restraining magnetic circuit, the ratio of operating to restraining ampere-turns giving tripping current in the relay remains fairly constant over a wide range. From this it is clear that any ratio of operating to restraining excitation greater than that indicated by the slope of

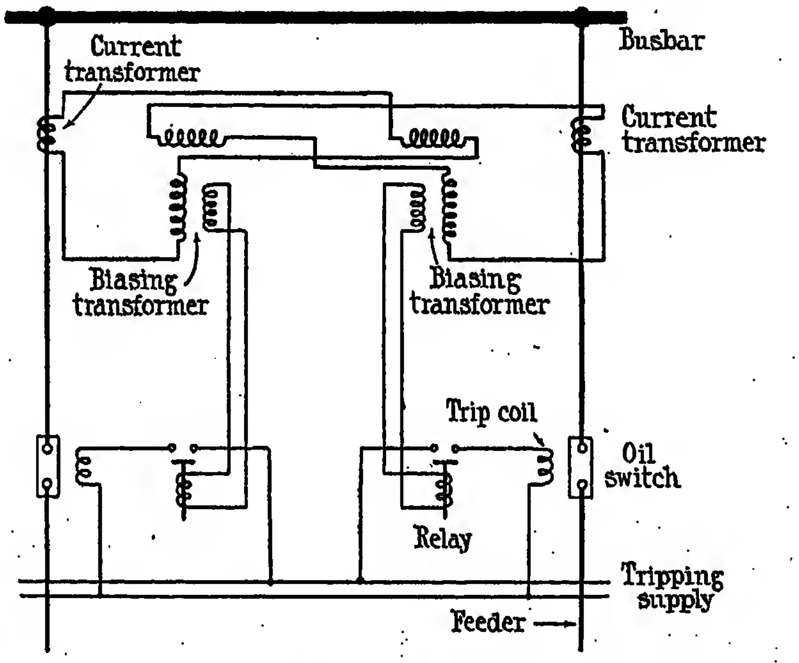

Fig. 7.—Discriminating circuit with biasing transformers.

this curve will provide a current in the secondary circuit more than sufficient to trip the relay, whilst any ratio less than that shown will not cause the relay to operate at all.

In Fig. 8, therefore, are shown curves connecting relay current with operating current, a restraining current having direct proportional relation to the operating current being simultaneously present. Each curve refers to a different ratio between operating and restraining excitation.

If the value of current at which the relay is set to trip is that indicated by the dotted line, the curve of secondary current due to a ratio as in Fig. 5 would, except in the neighbourhood of zero excitation, lie along this line. It was pointed out, however, in regard to Fig. 6 that when the two circuits are carrying equivalent currents the operating and restraining currents in the coils of each relay are likewise of similar magnitude; the same state of affairs exists in connection with the operating and restraining windings of the biasing transformers in Fig. 7.

Evidently, therefore, it is possible to provide biasing transformers having such operating and restraining turns that, when excited in series, there will be set up in the secondary winding and relay, a current as indicated by curve (*a*) in Fig. 8, which shows the actual characteristic obtainable.

It was further seen in connection with Fig. 6, and present in the appropriate relay. In the previous case it will be recalled that under circumstances when the operation of a relay would be incorrect the only operating current would be that due to imperfections of balance.

The connections in Fig. 7 indicate that this requirement is met by the arrangement shown, since under all possible fault conditions there will be present in

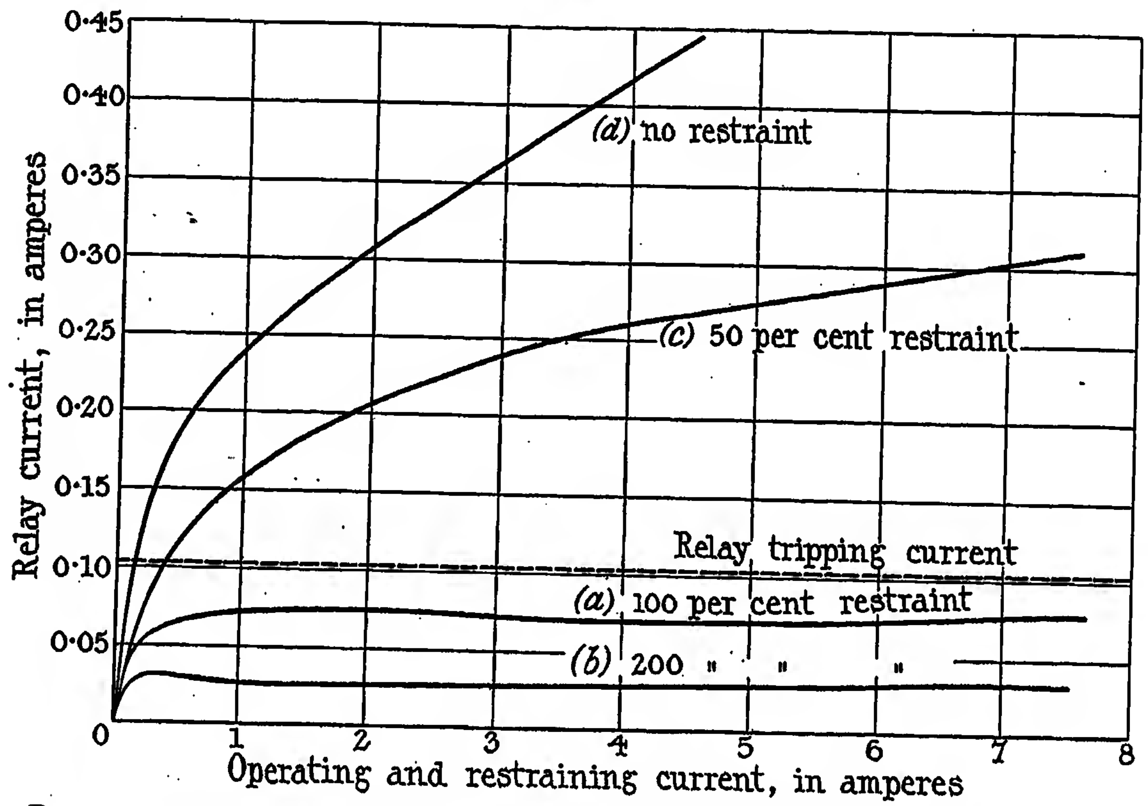

FIG. 8.—Characteristic curve of biasing transformer; discriminating restraint.

accordingly it applies to Fig. 7, that on the occurrence of a fault on one of the circuits there will be an operating current exceeding its restraining current in the biasing transformer associated with the defective line, whilst on the sound feeder the restraining current will be greater than the operating current. In Fig. 8 the latter circumstances are illustrated by curve (*b*) and the former by curve (*c*).

In the extreme case of a severe fault on one circuit with no current flowing in the other, there would of course be no current in the relay which trips the latter, whereas in the other relay there would be a secondary current in accordance with curve (*d*) in Fig. 8, which is simply that of unrestrained transformation. As indicated in the previous section, however, the relay would receive only a limited current no matter how severe the fault current might be, being thereby protected from mechanical or electrical damage under such circumstances.

In connection with the provision of overload restraint, the effect of a phase difference between the operating and restraining excitation has been referred to, when it was pointed out that the magnitude of the restraining effect was not always of great importance provided that it was sufficient to serve its purpose. In the present instance it is essential that where it is necessary for a relay associated with a sound circuit to be restrained from operating under fault conditions, this restraint shall be of a definite nature, since an operating current due to that carried by the sound line will be the defective circuit a resultant current containing a component equal to, and in phase with, that in the sound line.

Fig. 6, however, does not represent the most advantageous method of protection on these lines, as such an

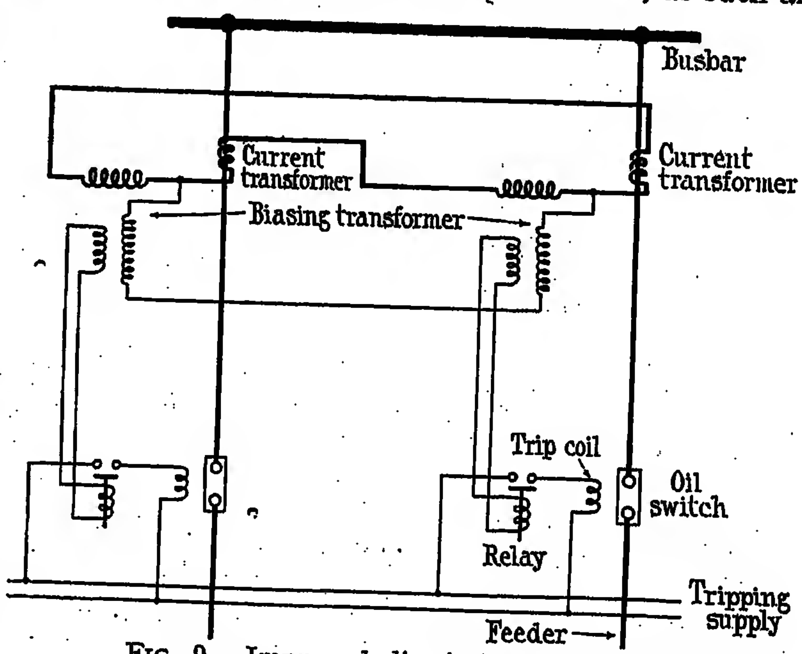

FIG. 9.—Improved discriminating circuit.

arrangement operates on a constant difference current. The superior merits of a system operating on a value of difference current increasing in accordance with the transmitted current or through load have previously been pointed out.

In order to endow the scheme shown in Fig. 6 with such properties it is only necessary to provide a restraining effort exceeding, for equal exciting current, the operating force. This may be arranged by providing an increased number of turns on the restraining coil, or by slightly adding to the length of the relay beam between the fulcrum and the point of attachment of the restraining plunger. The author has found that the latter gives a more extended range of truly proportional bias, as this effect is likely, in the former instance, to be restricted by saturation of the plungers. This arrangement, it is believed, constitutes the first known example of a biased system of protection and is due to Mr. Wedmore.

Instead of a scheme on the lines of Fig. 7, the author employs the arrangement shown in Fig. 9, which gives both discriminating and overload restraint. The current transformers and restraining windings are connected so as to form a circulating-current circuit having equipotential points across which the two operating windings are connected in series. The restraining windings, it will be noted, are cross-connected.

Unlike the arrangement shown in Fig. 7, the connections indicated in Fig. 9 ensure that no current will appear in the operating windings when both circuits are sound, except such as may be due to lack of balance on the part of the current transformers or the primary circuits themselves. On the occasion, however, of a short-circuit on some other part of the system being fed through the circuits protected, and due to which unbalancing may be in evidence, correspondingly heavy currents will be set up in the restraining windings. The property of overload restraint is thus seen to be present.

The properties of discrimination of this scheme are, however, very similar to those provided by the connections shown in Fig. 7; on the occurrence of a fault on one of the protected lines a corresponding difference current will appear in both operating windings. It is clear that the presence of a heavy short-circuit on the one line, there being no current in the sound primary circuit, represents the most severe condition for discrimination, and under these circumstances the difference or operating current is equal in magnitude to that in the restraining winding on the biasing transformer controlling the relay on the sound line.

Relations similar to those described in connection with Fig. 7 are employed between the operating and restraining windings, and accordingly Fig. 8 will also be applicable to this circuit. The biasing transformers associated with the sound line, therefore, have equivalent operating and restraining currents and will in consequence, in accordance with curve (*a*) in Fig. 8, remain inoperative. The transformer controlling the other relay, whilst receiving the same operating current, will be unrestrained and will therefore trip, thus disconnecting the defective circuit from the system.

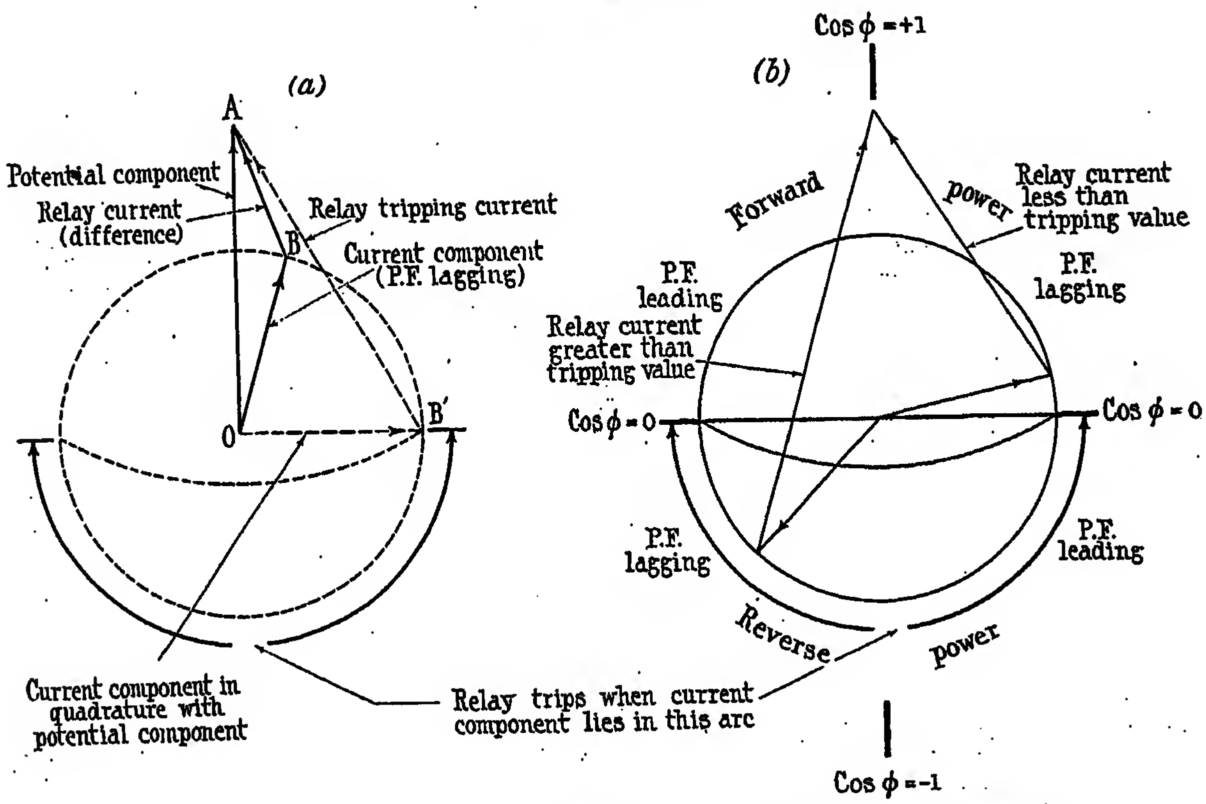

FIG. 10.—Vector and polar diagrams illustrating directional operation.

Attention is directed to the fact that in any biasing transformer protecting a healthy line, the operating current appears in its restraining winding when a fault occurs. Hence the restraining excitation is in phase with the operating ampere-turns.

Circulating-current circuits operating on the above principle may be arranged for protecting any number of parallel circuits.

In the arrangements described in regard to the protection of double circuits it is evident that if one of the lines trips out, no measure of discriminating protection may be applied to the remaining circuit. In practice, means of automatically rendering the protective gear inoperative if either switch be open would be arranged.

In schemes involving more than two lines it will be

necessary to provide auxiliary switches which, in the event of one line coming out of service, will so modify the circulating-current circuit that it remains effective for the protection of the reduced number of lines.

(3) *Directional discrimination.*—Existing methods of directional discrimination usually make use of one of two operating principles. The former of these, in which the relay is actuated by the reaction set up between two windings, one of which is excited by current and the other by potential, necessarily employs relays of appropriate type, usually of dynamometer form. The other principle involves the vectorial addition or subtraction of electrical effects set up respectively by current and potential excitation, some means being devised for arranging that neither current nor potential alone can effect operation of the relay.

The latter principle has been applied by the use of balanced-beam relays, and, as may be anticipated—following the use of the biasing transformer in lieu of this type of relay for other purposes—it is possible to employ a biasing transformer, controlling a simple relay in an analogous manner.

Whilst this principle is not capable of quite the degree of precision attainable with the dynamometer type, it is thought to possess some sphere of usefulness.

If it be supposed, for the purpose of explanation, that the voltage and current concerned be of constant magnitude, a means of arranging directional discrimination, within the specified limitations, by means of a simple relay having current and potential windings, is immediately apparent. It might be carried out, for example, on the lines indicated in Fig. 10, in which OA represents the vector value of the potential excitation, which it is convenient to consider as being of fixed position, and, by hypothesis, is of constant length. OB represents the current vector, also of fixed magnitude but having a varying phase relation to OA, according to the conditions of power. The excitation of the relay, being the resultant of OA and OB, will vary between the limits of the arithmetical sum and difference of these two quantities, and is represented by the vector AB.

This arrangement will possess directional properties if the relay be set to trip at a value equal to that of AB′ when the current and potential are in quadrature, under which circumstances AB′ will form the hypotenuse. If the connection be made so that addition occurs when the direction of power is negative or reverse, the relay tripping current will be reached whenever there exists a negative component in the current. In practice, however, we are concerned with both potential and current of varying magnitudes, and the above scheme is clearly inapplicable; it could only be employed were some means available of obtaining an excitation related to the current or pressure in direction but not in magnitude.

The possibility of this is suggested by the form of curve (*a*) in Fig. 8, and it has in fact been found possible, by a suitable design of windings and magnetic circuit, to provide a biasing transformer which, with series-connected operating and restraining windings, will maintain in the relay a current approximating very closely indeed to the mean value, this being maintained over a current range extending from a small fraction of full load to the maximum possible overload.

If the assumption be made that the potential will always be of constant value, only the current excitation need be provided through the medium of a biasing transformer. The relay would then be furnished with a separate winding, energized in series with a resistance large in comparison with the reactance of the winding, with a view to the provision of a current in phase with the potential. Advantages accrue, however, if the potential excitation be also provided by means of a biasing transformer, a simple relay being employed having one winding only, connected as shown in Fig. 11.

In this figure it will be noticed that the relay is excited in series with the secondaries of two biasing transformers, one of which receives the secondary current of the current transformer whilst the other

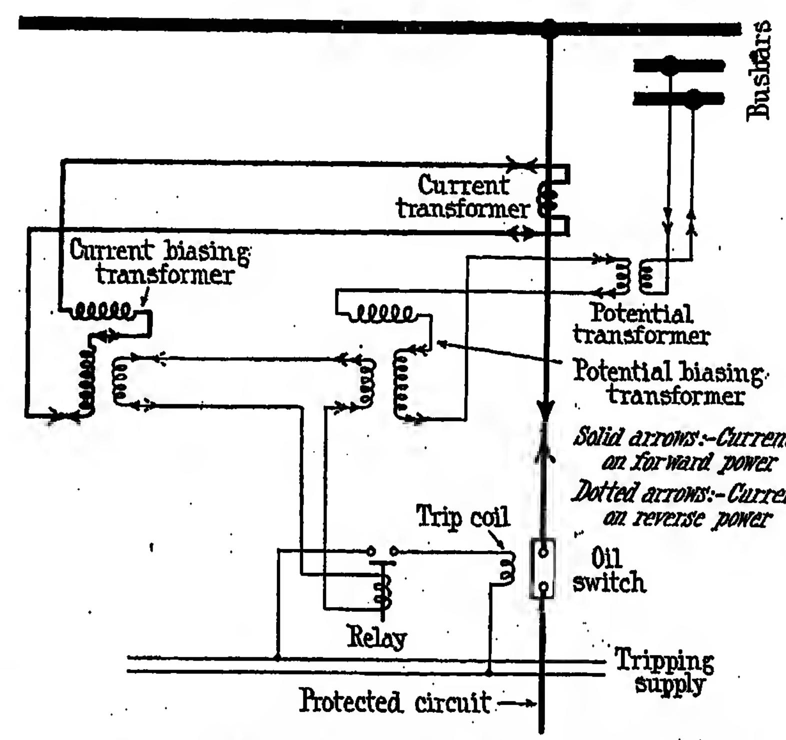

FIG. 11.—Directionally operating circuit with biasing transformers.

derives its energy from the secondary of a potential transformer. The relay will accordingly trip when the resultant secondary current of the biasing transformers reaches the appropriate value in the manner described in reference to Fig. 10.

If the arrangement be excited from the current transformer only, the relay current would be in accordance with curve (*a*) in Fig. 12, which is seen to be similar to curve (*a*) in Fig. 8, except that in this instance it may be desirable to provide as flat a characteristic as possible.

The relation between the relay current and the potential may now be considered, it being supposed for the moment that no energy is derived from the current transformer. Apparatus of this nature will essentially be more commonly associated with polyphase circuits than with others, and the present example is intended to be applied to an ordinary three-phase system.

In directionally functioning apparatus it is now the accepted practice to excite the potential windings from phases adjacent to those in which the corresponding current elements are connected, in order to overcome

difficulties due to vectorial distortion of the potential under short-circuit conditions, which difficulties are known to occur if this principle is not adopted. It will be seen that the present arrangement is peculiarly suitable for carrying out this requirement, for the following reasons.

Where the above practice is carried out it is clearly necessary to arrange that the potential relay current shall be in quadrature with the voltage producing it, in order that at unity power factor there shall be coincidence of phase relation between the current and voltage effects. Where dynamometer relays are used, the pressure coils are sometimes excited in series with condensers for this reason.

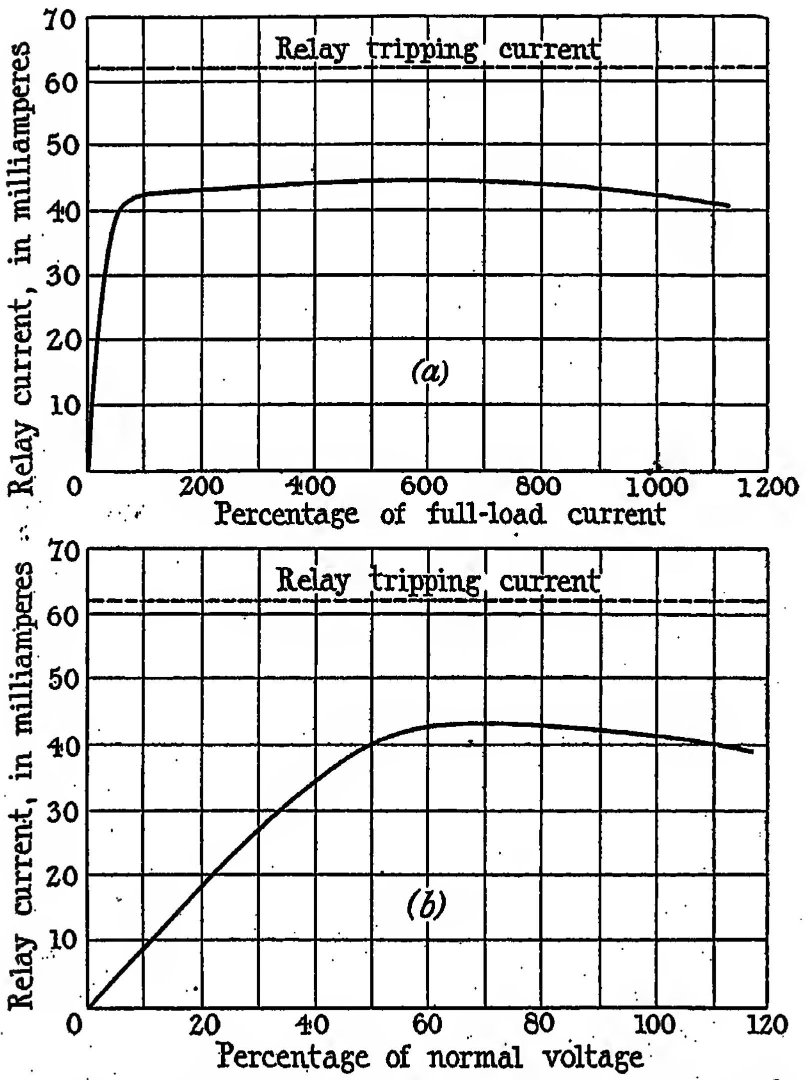

FIG. 12.—Characteristic curves of biasing transformer; directional operation.

In Fig. 11 it will be observed that the potential biasing transformer, as well as that excited by the current transformer, has operating and restraining coils connected in series. Since the restraining winding has more turns than the operating winding, and, moreover, since it is of a more highly reactive nature, due to the absence of any associated secondary winding, its impedance will very greatly exceed that of the latter, with which, it is to be noted, it has no inductive relation. The phase relation of the current in the operating winding to the potential from which it is derived, will accordingly approximate very closely to quadrature. If, therefore, the above method of potential connection be adopted, the proper conditions are accordingly obtained.

Whilst the characteristics of the potential biasing transformer may be arranged to be similar to curve (*a*) in Fig. 12, it may be preferable to arrange them after the pattern of curve (*b*), for the reasons explained below.

It will be seen that the effect of the flat characteristic will be such that if any point on the curve be chosen to represent normal pressure, a reduction in voltage due, for instance, to a fault on the system, will not cause a proportional decrease in the relay current, only that current derived from the potential being considered for the present. The shape of curve (*b*) in Fig. 12 will enable more sensitive operation to be obtained on reduced pressure, whilst the falling-off of current on over-voltage is likely to have a favourable effect on the performance of the apparatus when subjected to surge effects giving rise to transient pressure-rises.

Whilst it is theoretically possible to provide unlimited compensation for extinction of voltage, in practice this will be limited by the capacity of the apparatus to withstand the heating effect of the current which is normally carried. To obtain adequate operating current at very small fractions of rated voltage, therefore, it is necessary to provide correspondingly increased ampere-turns under normal conditions. Similarly, it is possible

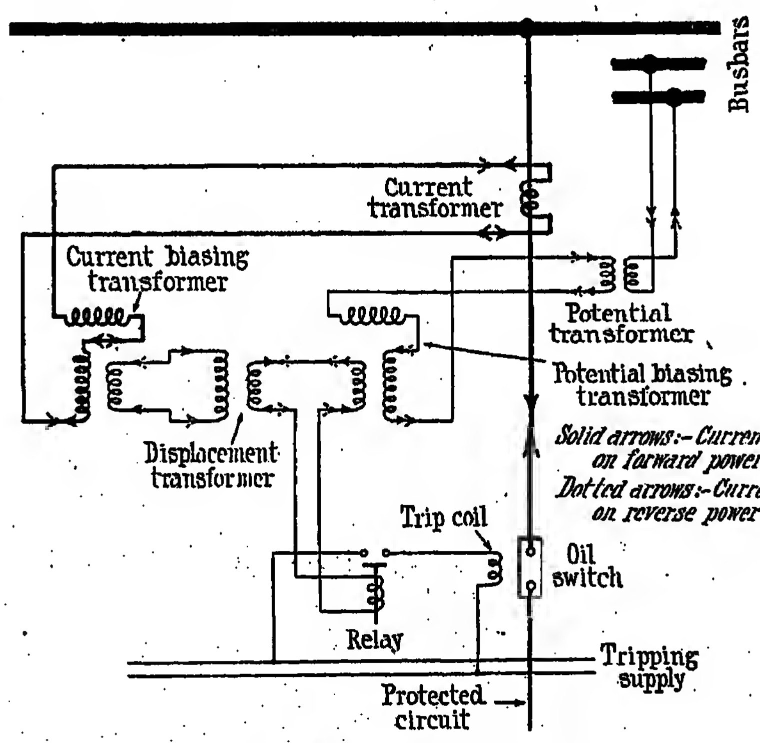

FIG. 13.—Improved directionally operating circuit.

to design the current element so that it will only be operative on currents not exceeding the rupturing capacity of any given circuit breaker. Alternatively, it may be designed to trip without potential on a sufficiently heavy short-circuit. Such an arrangement, therefore, will operate in accordance with the vector diagram shown in Fig. 10 (*a*), and its tripping characteristics may be more clearly exhibited by a polar diagram as in Fig. 10 (*b*). Here the full extent of angular relation between current and pressure and the respective portions of both, over which the relay is restrained and operated, are indicated.

The arrangement shown in Fig. 11 would probably possess a slight error due to internal losses in the poten-

tial biasing transformer, which would deflect the polar diagram slightly in a counter-clockwise direction, due to the fact that the potential current would lag behind the potential by an angle slightly less than 90°. This could be compensated for by connecting a resistance, taking a small fraction of the normal current, in parallel with the operating winding. This would cause the operating current to lag slightly behind the total potential current, thereby introducing the necessary correction.

A preferable arrangement, however, is illustrated in Fig. 13, in which an additional transformer is introduced between the biasing transformer excited by the current transformer and the relay. For reasons which will be more fully discussed in connection with the complete scheme of differential protection to be described in a subsequent section of the paper, this second transformation will usually be present in the form of a further these circumstances consists in the arrangement of the potential connections so that a phase displacement of the potential excitation in a direction favouring tripping on a reactive fault is effected. One method of carrying out this idea is the connection of the potential windings between line and earth instead of between phases, a scheme which introduces a displacement of 30°. This is not entirely effective, since on the occurrence of a single-phase fault very little difference in phase may actually exist between either arrangement; moreover, the presence of this phase-shift under normal conditions is of no advantage and might conceivably be detrimental in the event of any considerable leading current being found in the circuit protected.

In the scheme outlined in Fig. 13, however, the following phenomena occur, and give rise to a feature of utility. It has been explained how the presence of a second

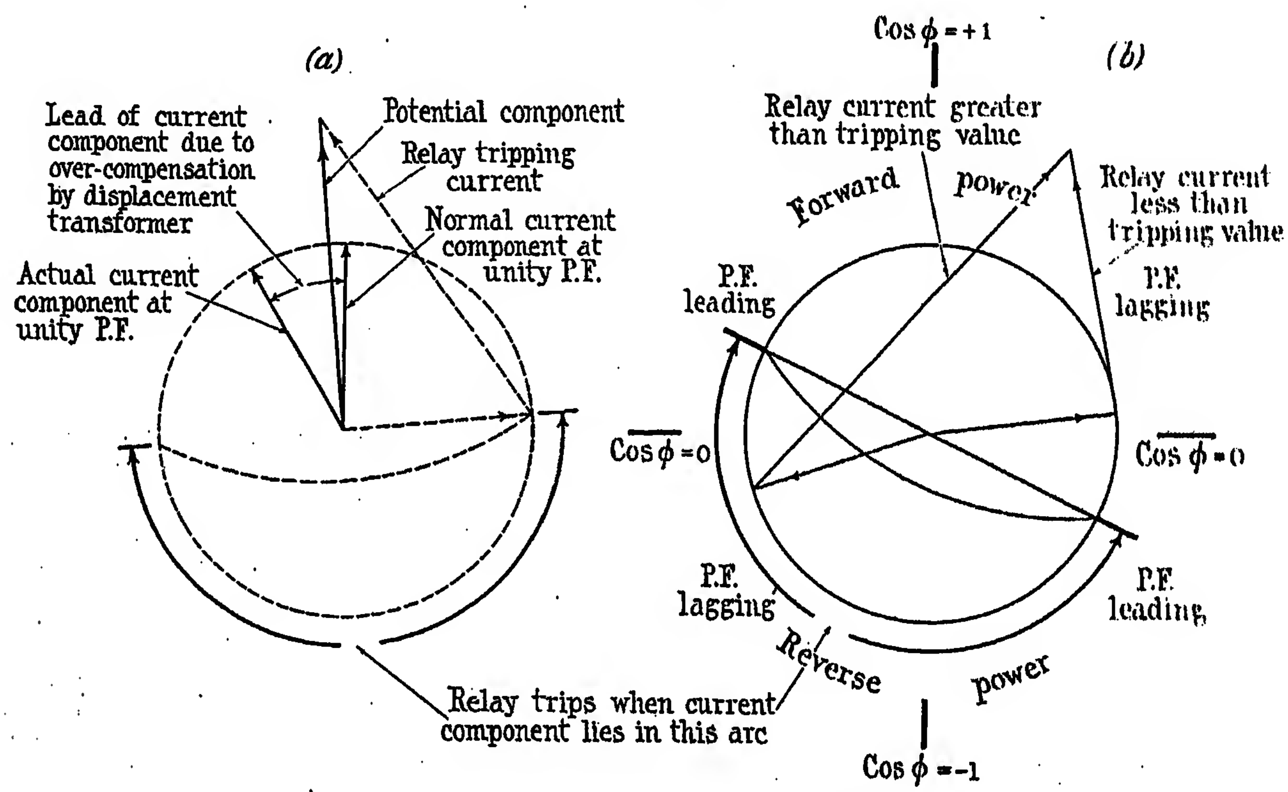

FIG. 14.—Vector and polar diagrams of improved directional circuit.

restraining effect, in directionally operative circuits of which the present simple diagram may form a portion. In Fig. 13, however, this is indicated as a simple transformation possessing no restraining feature. Under conditions of normal load this arrangement can be designed to have symmetrical tripping characteristics in accordance with diagram (*b*) in Fig. 10, without any additional resistance.

An additional feature of utility will now be discussed. It is well known that the majority of the more severe fault effects necessarily give rise to heavy lagging currents of low power factor, and in all forms of directionally discriminating apparatus this has been a source of difficulty, as such devices are necessarily not operating to best advantage under these conditions. Even more unfavourable to the present device are these conditions, since it is dependent for its property of acting directionally on a purely quantitative principle of operation.

A method of obtaining improved operation under transformation causes a corrective phase displacement giving correct tripping limits, as in diagram (*b*) in Fig. 10. It is found that on the occurrence of fault effects giving rise to heavy currents this effect becomes augmented in accordance with the magnitude of the current, so that under such conditions the tripping characteristics are as shown in the polar diagram (Fig. 14) rather than in Fig. 10. This gives the required feature in that under heavy-current conditions a current lagging by exactly 90° will give a greater relay current than one leading by precisely the same angle. In this instance the combined effect of both current and potential excitation is, of course, referred to.

This property, therefore, enables more definite discrimination to be achieved under the more difficult circumstances accompanying fault currents of low power factor and large amplitude, at the same time preserving accurate phase relation on currents of smaller magnitude, e.g. faults to earth on a system employing earthing

resistances. It will be perceived that with this arrangement it is not possible to vary the sensitivity of the apparatus by adjusting the relay setting, as it is upon this latter factor that the system depends for its discriminating features, and due to this inherent condition the precision of its operation will depend largely on the nature of the performance of the relay itself. Where it is required to provide variation in the value of the current necessary to operate the gear, a simple form of adjustable reactive shunt may be employed, or tappings may be provided in the operating windings. As previously indicated, it is realized that this device cannot be considered as a substitute for dynamometer relays in general; nevertheless there are often conditions where, due to lack of skilled maintenance or other local conditions, very simple apparatus may be preferred. Apparatus functioning on these lines might, for instance, be devised directly to trip the switch. In the more special systems of directional protection, shortly to be described, a simple relay operating on the above principle may always be employed. Alternatively, by using similar biasing transformers, and retaining all the special features to which they give rise, the simplest form of dynamometer relay or its equivalent may be used, should it be preferred. Each coil of the relay will be excited from the biasing transformer secondaries, which in the above case are connected in series.

(4) *Auxiliary restraint.*—In the circuits and applications described above, there has always been used in the restraining windings an alternating current of the same frequency as the operating excitation, the restraint depending for its magnitude on considerations associated with the conditions obtaining in the primary circuit, as, for instance, in the simplest case described, on the load carried by the apparatus or circuit protected.

A restraint of equivalent effect, not in fact dependent upon any questions of phase relation, might evidently be obtained by exciting the restraining winding from a source of direct current. In this manner a number of functions might be carried out on lines already familiar to switchboard and control engineers, e.g. practical requirements in connection with interlocking, signalling and similar schemes. Under any circumstances where the employment of a biasing transformer renders possible the use of a reduced number of contacts, the author suggests that its application is at least worthy of consideration. As an example, conditions sometimes arise when it is desirable simultaneously to put out of action for a brief period, or perhaps to render less sensitive, a considerable number of relays. To do this by ordinary methods might quite conceivably require as many contacts as there are relays, yet, if a device of the nature described be incorporated, all the restraining windings might be connected in series and energized from a single switch or relay contact. It might be possible in schemes of this nature, in which it is necessary to make dispositions in accordance with the closing or opening of circuit breakers, to utilize existing lamp-signal circuits. Many similar adaptations and devices will suggest themselves to those familiar with work of this kind. The object aimed at by the author in every case is the replacement, by static devices, of moving parts not associated with considerable amounts of power. In circuits where relays and biasing transformers are already employed for purposes of protection in accordance with the requirements previously described, the addition of controlling means on the above lines may clearly be carried out with facility, a further transformation being added to the existing circuit. It should be noted particularly that the loss in efficiency due to the second restraint is not so great as might be expected, the primary current necessary to trip a relay directly, with one transformation and again with double transformation being, in one practical case used by the author, in the ratio of 100, 120 and 140, respectively.

By controlling the value of the d.c. restraining excitation by means of a rheostat or other convenient apparatus, the tripping current might be remotely adjusted, and in stations where it is not possible to provide attendance of a very skilled order, adjustments of this nature might be preferably carried out in this manner, if they are frequently necessary, rather than interfere with the actual relay mechanisms. A simple example of direct-current restraint is illustrated in Fig. 22.

Construction of the Biasing Transformer.

The biasing transformer is built up in an entirely conventional manner exactly like any other type of small transformer suitable for outputs of the same order, that is to say, apparatus used in connection with instruments, etc., rather than with the supply of power.

In the majority of cases the core is made of punchings, assembled in the usual way, in former-wound coils. Where there is more than one winding situated on one limb of the core these are made up into one coil, suitable insulation being provided between the respective circuits. It is recommended that all coils be subjected to appropriate vacuum and impregnating treatments which, besides improving their insulating properties, render them less likely to break down due to mechanical causes, the process having the effect of solidifying them. It will be realized that in a complete scheme of protection a number of such elements may be employed. It is usual for all the elements necessary for a three-phase circuit to be assembled in a metal tank or other suitable receptacle, leads being brought out to conveniently situated terminals. The whole is then filled with compound. As this portion of the protective gear is under no circumstances energized by pressures exceeding that of the secondary of a potential transformer, and is more commonly associated with current-transformer connections at voltages, under normal circumstances, even smaller than the above, it would certainly appear that the section of the protective system which has discriminative properties could scarcely be provided in a form less likely to suffer deterioration of function from any cause whatever.

It is to be noted that since the biasing transformer is connected only in secondary circuits, it does not receive the full extent of any excessive primary currents, due to short-circuits, etc. It has been found possible to design the windings so that they may be

subjected, for testing purposes, to effects of equal magnitude to those arising in practice, without suffering damage. The tests may be made as often as required. This feature is very desirable in view of the importance of carrying out comprehensive and searching tests on protective gear.

Design of Protective Current Transformers.

The author does not propose to refer at any great length to this section of the protective circuit, as there would not appear to be any great conflict of opinion as to the objects which should be aimed at. The following brief notes, therefore, should suffice.

The most essential requirement in the design of apparatus to be installed as part of a protective system is that there must not be any feature likely to contribute towards risk of breakdown. Clearly, if the presence of any component of the protective gear introduces into the main circuit any hazard not otherwise present, the object of the apparatus is abrogated. Throughout the design of a protective transformer, therefore, both in regard to its insulation and to all other constructional considerations it is recommended that a more liberal factor of safety than that appropriate to lines of current transformers designed purely for energizing meters, etc., should be worked to. In the event of a destructive accident on a transmission system, the protective gear should obviously be the last portion of the plant to cease functioning. The use, for instance, of wound-primary current transformers for protective purposes is to be avoided, as this type is inherently more liable to damage on heavy short-circuits, both in regard to mechanical forces and destructive heating.

In every case, therefore, transformers of the bar-primary pattern are to be preferred. A straight primary conductor through opposite bushings is more desirable than the form associated with tank type transformers in which, although only one conductor may be employed, this is brought into the case through top bushings. With such a form of construction a partial loop in the primary circuit is unavoidable.

Within reasonable limits of dimensions and cost, an augmented secondary output, desirable for the reasons already given, should be sought rather by increase in the size of the iron core than by adding to the number of turns.

The reactive component of the primary impedance varies, at normal frequency, as the square of the primary turns and directly as the permeability of the magnetic circuit. A current transient of steep wave-front encountering such a transformer will, however, set up across its terminals a local pressure-rise not necessarily in accordance with the above relation. Under such conditions one would expect the flux set up in air paths by disturbances of this nature to bear a larger ratio to the total induction than would be the case at working frequency. If these aspects be considered, the advantages of a large core and single conductor as compared with an arrangement capable of equivalent sensitivity (so far as protection is concerned), and having less iron and more turns, will be self-evident.

Protective Relays.

General.—In the protective schemes dealt with, which only require a relay of simple type, any desired form of relay may be employed. The attracted-armature relay is one of the most suitable, chiefly because, for given excitation, it can develop an operating force considerably greater than any other type of a.c. relay. Moreover, a relay of this form employs the minimum amount of movement and consequently is less likely to be affected by frictional effects than types involving greater displacement of the moving parts. It is possible, indeed, to design a relay on these lines without pivots, since the movement of the armature is confined to a few degrees of arc.

Anti-surge device.—In most instances it is a decided advantage that the speed of operation of the attracted-armature relay is probably greater than that of any other type. It is, however, sometimes desirable to render such a relay immune from operation due to

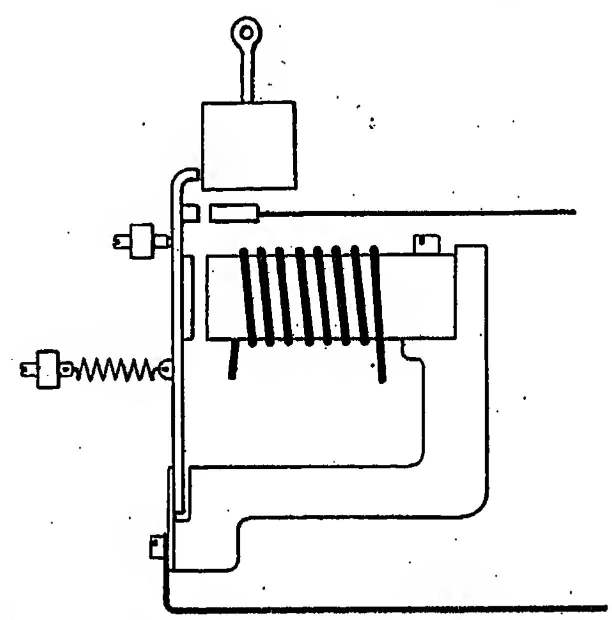

Fig. 15.—Attracted-armature relay with anti-surge device.

sudden impulses not sustained for more than two or three periods. Loading the armature delays the tripping of the relay but does not prevent it operating on a transient, as the moving system acts like a ballistic pendulum and stores up the energy due to the sudden impulse.

Instead of increasing the mass of the armature a suspended weight may be added, as shown in Fig. 15. This weight hangs free of the armature but is displaced when the latter operates.

Only an operating current sustained for something of the order of 0·1 sec. will then trip the relay. If the impulse is of shorter duration the armature will be observed to strike the weight a sharp blow and to make no further movement. The energy due to the transient is transmitted to the weight, the movement of which may be seen to persist after the operating current has ceased.

Augmented contact pressure.—In relays of a sensitive nature it is usual to employ some means of augmenting the contact pressure when the trip circuit has closed. This generally leads to a certain amount of complication in the construction of the relay, but the desired

feature may be simply contrived on the lines indicated in Fig. 16.

The magnetic circuit associated with the operating winding, it will be perceived, resides entirely in the upper section of the core and armature, as indicated by the chain-dotted lines. The contacting winding is wound up with the operating coils, but is connected in a different manner so that each limb of the core is excited in the same sense. This will result in a flux being set up by this winding, existing not only in the upper part of the core but also in the lower portion. This flux is shown by the broken lines. It will thus be seen that the provision of the contacting winding does not entail any further mechanical complication. It should be noted that the a.c. and d.c. windings must be mutually non-inductive, or the relay may vibrate synchronously.

Resonant protective relay.—Compared with d.c. protective relays it is particularly to be noted that the a.c. relay is at a disadvantage on account of its low power factor. In the d.c. relay the exciting ampere-turns are only limited by the available winding space.

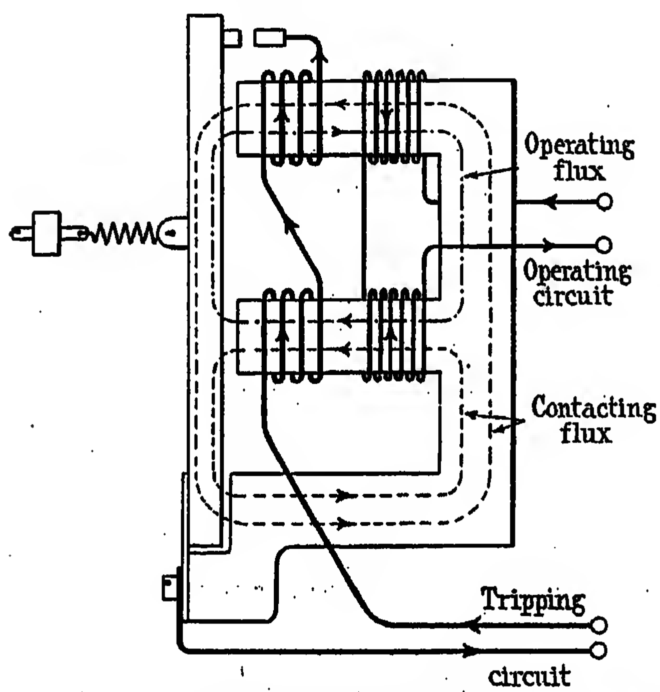

Fig. 16.—Simple attracted-armature relay with augmented contact pressure.

On the other hand, the a.c. relay is subject to the limitation imposed by the reactance of its windings. If any given relay be operated with alternating current and again with direct current, the volt-amperes being the same, the relay in the latter case will receive excitation several hundred per cent in excess of that possible where alternating current is used. Thus the force exerted by the relay when energized by direct current is correspondingly greater.

This point of view suggests that it may be possible to bring about an increase in the operating force of an a.c. relay if means be provided to increase the power factor. This may be done by utilizing a resonating capacity connected across the relay terminals. Such a condenser, however, if suitable for a current-operated relay might be expected to be of very considerable dimensions, and a preferable arrangement is illustrated in Fig. 17, in which a secondary winding is provided, directly connected to the condenser, on the relay. The number of turns on this winding may be chosen so that a condenser of small bulk will fulfil the requisite conditions. If this condenser be built into the relay assembly no complications will be introduced so far as the installation of the gear is concerned, and, provided that the secondary pressure cannot exceed, say, 50 to 100 volts, there is no reason why such an arrangement, which is only concerned with a few volt-amperes, should not prove reliable.

Whilst it is realized that the addition of the extra complication might not be welcomed were the object the achievement of specially small fault settings, it is suggested that the possibility of the use, for any given sensitivity, of a larger and heavier relay and increased operating force may be worthy of consideration. It is found that without what may be described as "close tuning," such that the operation might be affected to a serious extent by normal frequency variations, a reduction of 60 per cent or more may be achieved in the volt-amperes necessary to cause operation of a relay.

For a given primary current, the protective transformer is capable of providing a definite maximum output in volt-amperes. The latter is not affected by the power factor of the relay forming the secondary load.

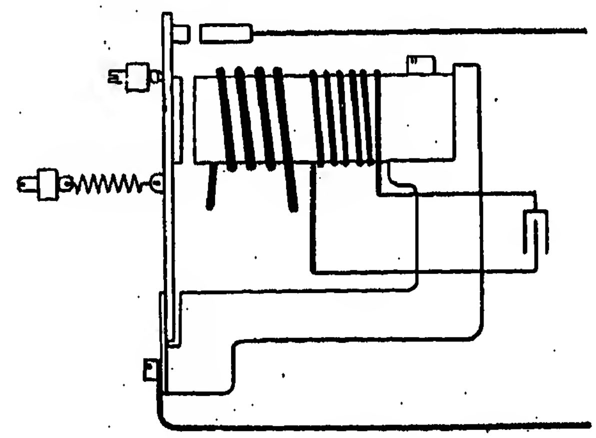

Fig. 17.—Resonant relay.

On the relay being called upon to clear a fault of such severity as may cause a considerable drop in the speed of the generating plant, ample tripping energy will be available even though the relay operate at the current value at which it would trip were it not resonated. Such a relay would also be less affected by any transient effects of the nature associated with steep wave-fronts or abnormal frequencies.

Other Components of a Protective Circuit.

The author has dealt at varying length, according to their novelty, with the relays, current transformers and biasing transformers comprising the apparatus present in protective circuits of the nature embraced by the present paper, and, as will be seen, very little further apparatus is required. There will, however, in certain instances be a few further items, of a general nature, but installed for purposes purely associated with the protective gear. The considerations relevant

to the design of protective transformers, relays, etc., discussed above, should evidently apply to an equivalent extent to such miscellaneous components as are required to complete or assist the operation of the protective gear.

Obviously it is useless to expend great care on the design and installation of a protective system if there is the remotest possibility that the circuit breaker will fail to open when the tripping circuit is properly completed by the relay, due to such causes as failure of the supply of tripping energy. Moreover, in some systems it is essential that certain auxiliary switches should be provided on the circuit breakers, and in such cases the proper operation of the protective gear is just as much dependent on these as on the relays. Accordingly they should be in no way less reliable. It does not follow, for instance, that an auxiliary switch designed for operating a signal lamp is equally suitable for incorporating in a protective circuit.

Apart from questions of reliability and general robustness of design, it is usually necessary for auxiliary switches operating in protective circuits to open or close their contacts at a more definite instant in the stroke of the switch than is required of apparatus having a more general application. Where there is present, in a protective circuit in which provision is made for any form of core balance or leakage protection, a three-phase auxiliary switch, the simultaneous operation of all phases will be a point requiring atten-

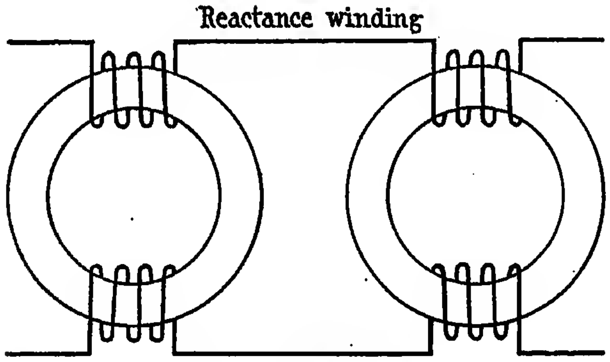

FIG. 18.—Phantom auxiliary switch.

tion, lest it be possible for transient leakage effects to be set up due to one contact being made before another, no real leakage component being present.

Whilst it will no doubt be agreed that systems of protection not requiring auxiliary switching are to be preferred to schemes necessarily involving this feature, there are unquestionably certain occasions when, due to cost or to the impossibility of applying the preferred arrangement, such devices must be adopted.

For these reasons it must be admitted, therefore, that the employment of automatic switching means, other than the conventional and necessary arrangements concerned with the operation of the circuit breakers, must constitute a definite addition to the attention necessary to maintain such a system in a state of efficiency.

A further objection to the installation of such devices is often encountered in the presence, on the oil switches concerned, of auxiliary switches associated with other requirements, e.g. interlocking or signalling. Under such circumstances the provision of further contacts may be impossible or at any rate difficult and undesirable. These restrictions have led the author to consider whether, where no alternative to the installation of additional auxiliary contacts appears to present itself, some means may not be devised for reducing the number required or for simplifying the arrangement by applying the principles utilized for reducing the complication of the protective apparatus itself. Where the requirement to be met is simply to ensure that certain relays shall be inoperative in the event of corresponding switches being open, this may be achieved by an auxiliary direct-current restraint, operative from existing signal or other contacts. This would involve only the addition of extra elements in the biasing transformer, and two extra terminals. As all three relays in a three-phase arrangement would be controlled by the one d.c. circuit, some simplification would result.

This, however, will not meet every case, because it is sometimes essential that, on the opening of an oil

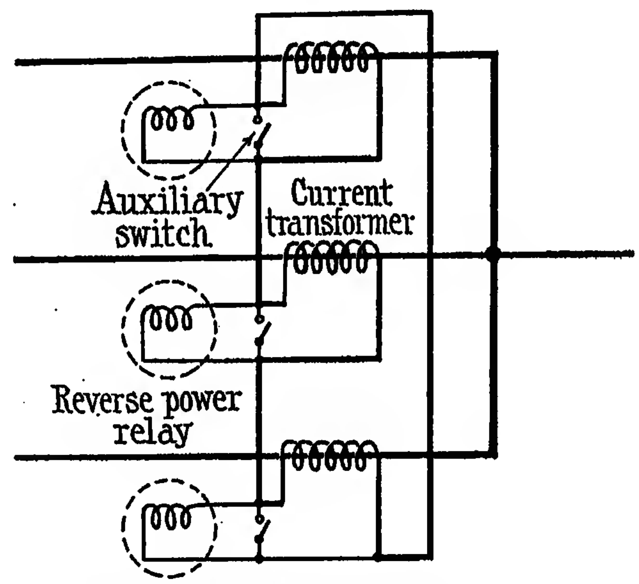

FIG. 19.—Typical protective circuit.

switch, appropriate modification shall be made to the a.c. secondary circuit, idle current transformers and windings having to be short-circuited in order that they may not interfere with other portions of a circulating-current circuit. For such a purpose it would certainly appear that an actual switch contact forms the only possible solution. The author has, however, carried out experiments with a device intended to perform this function, and this has given very favourable results.

Phantom auxiliary switch.—The particular line of attack is suggested by considering a switch as an impedance capable of being varied, theoretically, between zero and infinity, and in practice over a suitable range. Investigation shows that in a secondary circuit excited by current transformers of conventional design, the correct relation of the equipotential points in a circulating circuit may be maintained, on a portion of the circuit becoming inoperative, if a device capable of

undergoing, at will, a change in impedance in the ratio of about 1 : 250, is substituted for an actual auxiliary switch contact.

As the permeability of magnetic steel is variable between limits of this order, according to the flux density at which it is operated, use may be made of this material in a reactance.

If the secondary winding be omitted from the pair of ring cores shown in Fig. 1 (*a*), an arrangement as outlined in Fig. 18 results, the operating winding having an impedance varying with the induction in the core. The reactance curve of any ring core shows an increase of reactance with exciting current up to a certain sharply defined maximum, after which it becomes reduced, rapidly at first, but more slowly with further increase in current.

previous maximum value, so that only negligible currents can flow through the parallel circuit.

It is to be noted that here, as in the previously described scheme, all three phases may be controlled by one d.c. contact, which may possibly be necessary for other purposes. In this case no additional auxiliary switch will be called for. This arrangement ensures simultaneous operation on all phases, thus avoiding the effects in leakage circuits to which reference has been made. The control of a direct current of the necessary magnitude, not usually exceeding 1 ampere, may quite possibly entail less severe service on the control contact than on a similar one liable on occasion to carry secondary currents corresponding to primary overloads or short-circuits.

Again, the "phantom switch" device may be built

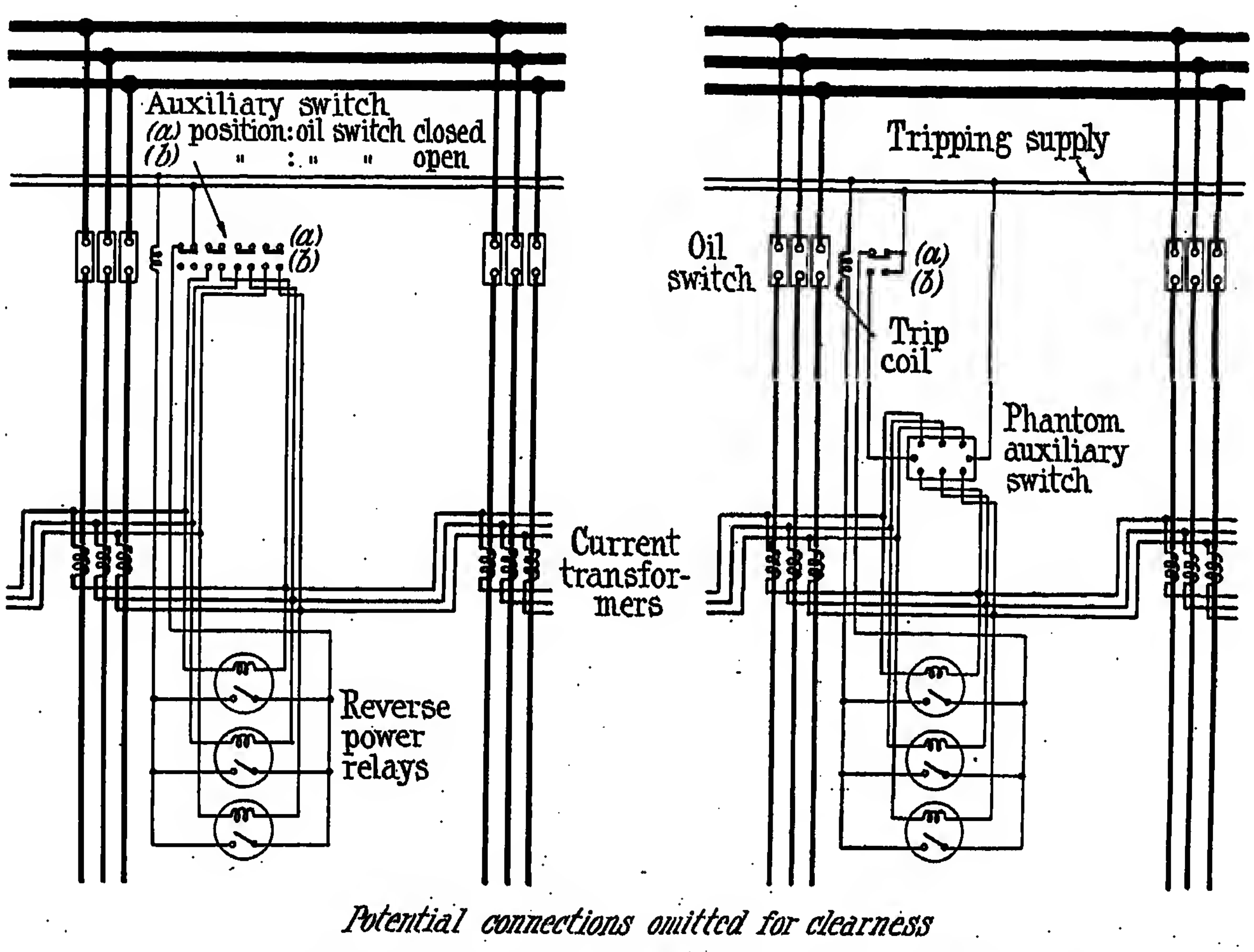

FIG. 20.—Application of phantom auxiliary switch to protective circuit.

The winding above referred to, which may more correctly be called the reactance winding, is placed in circuit in lieu of the switch contacts. If the turns and cross-section are so selected that under the maximum voltage to which it can be subjected its reactance is still on the rising portion of the curve, and if the reactance is correctly apportioned in relation to the circuits with which it is connected in parallel, it passes only an inappreciable current. The winding referred to in Fig. 1 as the restraining winding, which, it will be recalled, is not inductively related to the other winding, is capable of saturating both cores. In the event of its being necessary, in effect, to "close" the switch contact represented by the reactance winding, the saturating or control winding is excited by direct current. The impedance of the short-circuiting winding will immediately be reduced to about 1/300th of its

into the biasing transformer case, and similarly compound-filled if desired. This results in a distinct simplification of the actual wiring.

Complete protective systems or circuits in which the application of the biasing transformer is shown are given in Section 2, but the practical result of the use of this device may be illustrated in connection with another typical protective circuit.*

Fig. 19 shows a single-line schematic diagram of a method of parallel-feeder protection using differentially connected reverse-current relays. For the sake of clearness in this and the succeeding diagram, potential connections are not shown, the current transformer secondary connections only being relevant to the matter under discussion.

The actual wiring diagram involved on any one of

* See *Journal I.E.E.*, 1920, vol. 58, p. 395.

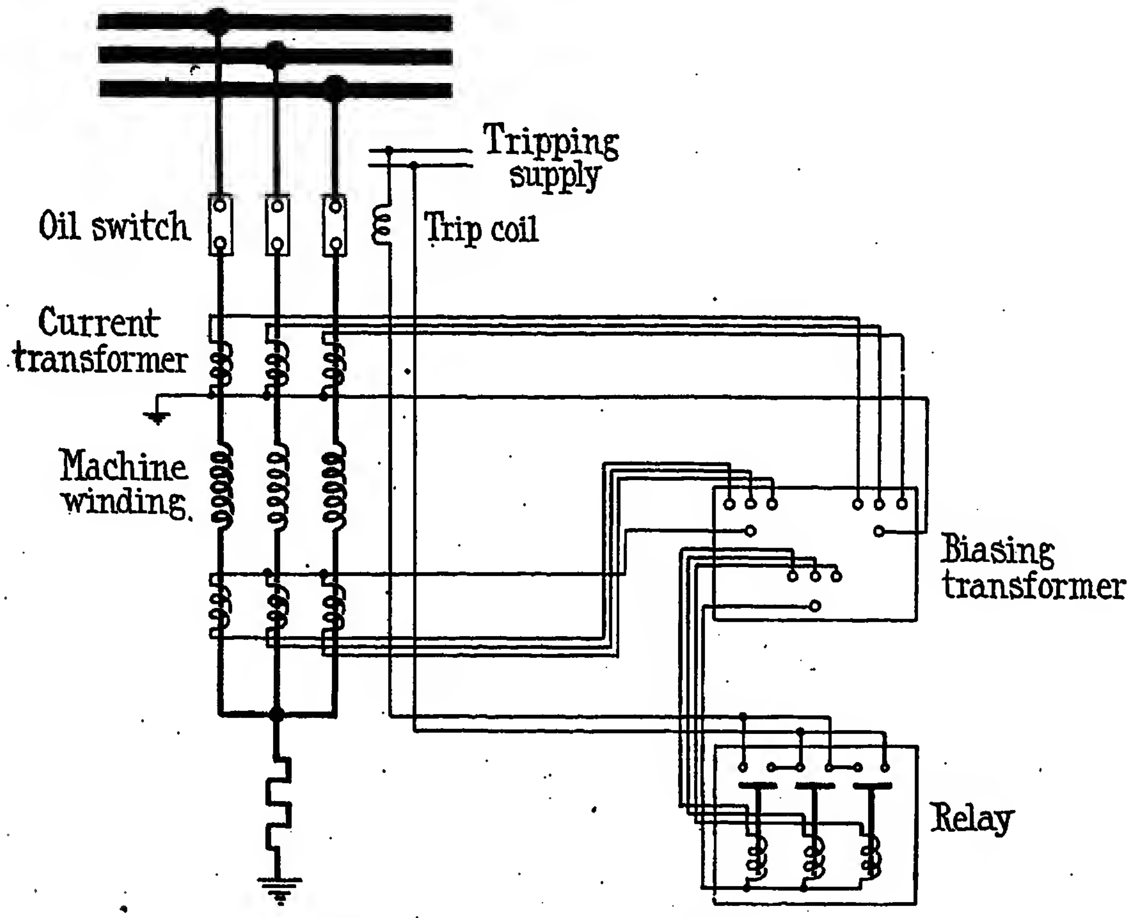

FIG. 21.—Generator protection.

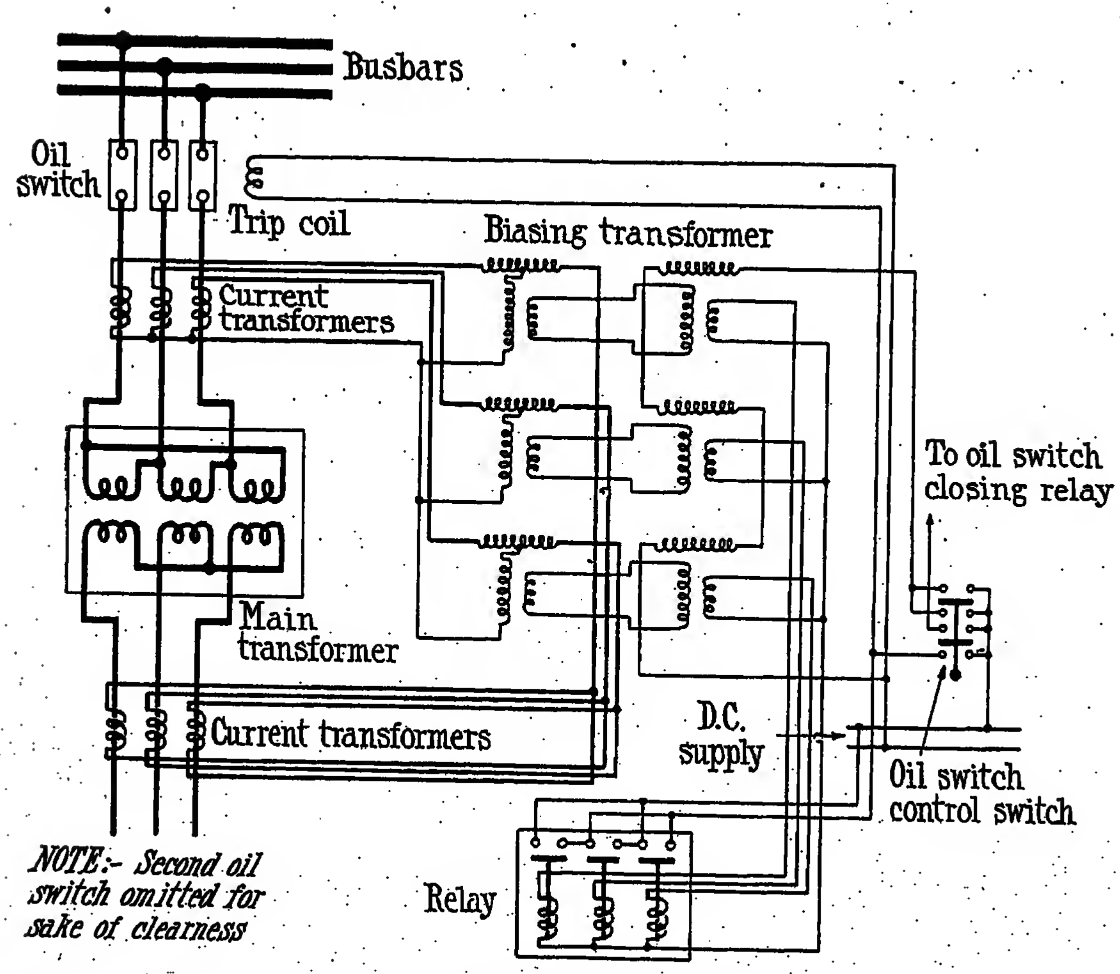

FIG. 22.—Transformer protection.

the above feeders might be expected more or less to resemble that shown in Fig. 20, in which both the use of ordinary auxiliary contacts and the corresponding arrangement with the alternative device are illustrated.

Apart from the fewer contacts involved, it is possible in installations of considerable extent that the cost of the static device may be more than compensated by the saving in cable. Where a number of lines are concerned, common control connections are evidently possible, according to the usual practice in regard to trip circuits, etc.

Section 2.

Protective Systems.

General.—It is now proposed to describe in greater detail the application to various protective circuits of the apparatus dealt with in Section 1.

In the case of each individual piece of apparatus, stress has been laid on the desirability of maintaining the utmost simplicity in construction. Clearly the same considerations apply to an enhanced extent to the complete protective circuit.

In the systems to be described the author has more particularly had in mind the simplification of the installation and maintenance of the gear. All connections involving phase relation and polarity are permanently made, as far as possible, in the biasing transformer itself. The complete assembly of all the units required for the various functions of a three-phase circuit is referred to by the latter term.

Typical practical wiring diagrams are given in certain instances, in addition to explanatory figures in order to indicate these characteristics.

Generator protection.—The method of application of a biasing transformer to the protection of a single winding has already been described with reference to Figs. 3 and 4. The protection of generator windings will therefore be carried out on similar lines and is shown in Fig. 21, which is self-explanatory.

Transformer protection.—The protection of transformers on the circulating-current system is carried out on very similar lines to the protection of a generator. The effect of the magnetizing current, however, has to be reckoned with, more particularly at the instant of switching on, when, as is well known, a transient of considerable amplitude usually occurs.

A very simple method of rendering the apparatus less sensitive during the switching period may be provided by the use of an auxiliary d.c. restraining feature as described in Section 1.

Instead of a biasing transformer containing three cores as in Fig. 21, one having six units, as in Fig. 22, may be used. Under normal conditions the additional biasing cores, which are connected between the relay and the secondaries of the overload restraining units, act as a simple transformer, since the restraining windings are not energized. These are connected to the d.c. tripping supply through an auxiliary switch on the main circuit breaker. This switch completes the restraining circuit while the circuit breaker is operating.

In the case of remotely operated breakers an auxiliary contact on the control switch may serve the same purpose. This arrangement is shown in Fig. 22.

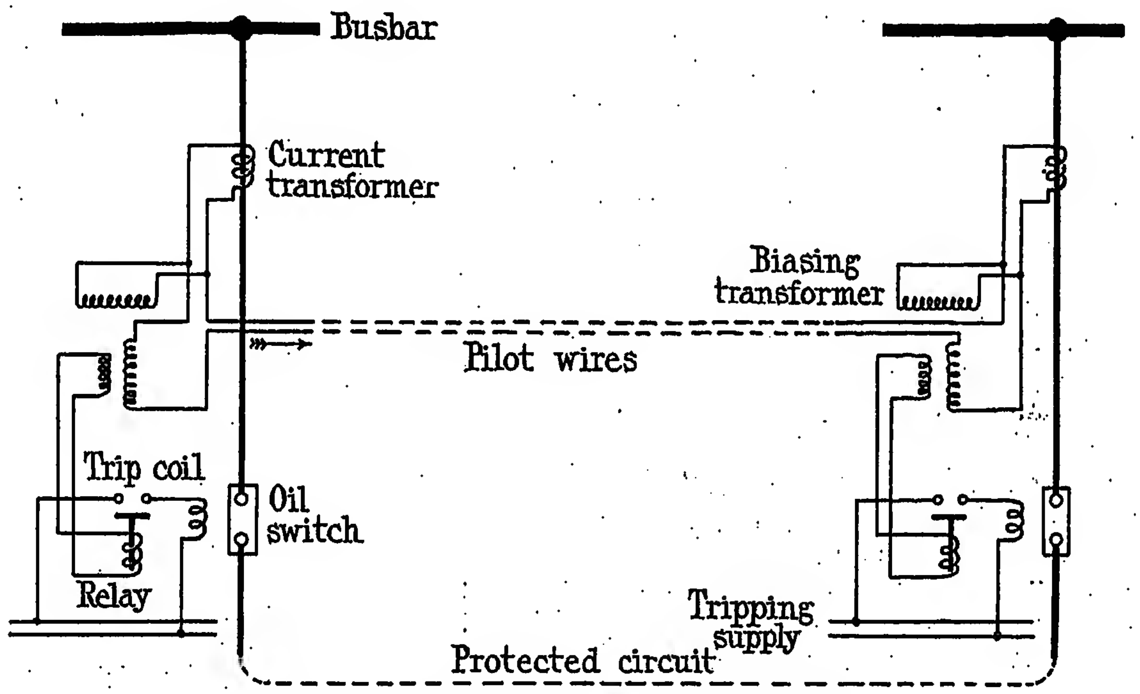

Fig. 23.—Opposed-voltage feeder protection.

Protective Systems for Single Feeders.

The opposed-voltage system.—This system of feeder protection has probably been more widely employed for the protection of single feeders, as such, than any other scheme. It has given excellent results within its sphere of utility, but difficulty is encountered in maintaining small fault settings on systems of large plant capacity, both in regard to accurate balancing and to pilot-wire capacity.

In order to avoid saturation of the transformers by normal load currents, and with a view to overcoming balancing troubles due to differences in the iron, air-gap transformers have been found necessary. Early types employing simple gaps gave rise to difficulties of

balance due to stray field effects, and ironclad designs having distributed gaps have been the most successful. Only when very great care in design is directed towards perfect and permanent balancing may satisfactory results be obtained.

The air-gap transformer, due to its inherently poor efficiency, is notably at a disadvantage in regard to sensitive fault settings, and very sensitive relays must be employed where this type of transformer is used. The capacity-current difficulty may be almost entirely overcome at some considerable expense by the well-known Beard-Hunter screening sheath.

The biasing transformer may be applied to an opposed-voltage circuit as in Fig. 23. Neither out-of-balance currents nor capacity currents are in evidence except under overload conditions when the restraining effect may also be arranged to be active. If sufficient restraint be provided to take charge of the maximum capacity current no very special accuracy of balance need be sought, as the former effect is likely to exceed the latter.

Discrimination between earth faults and line faults.—Better results may, however, be achieved by improved arrangements, on the lines suggested by Mr. Wedmore, who has pointed out that the demand for sensitive fault settings is necessarily associated with the isolation of earth faults. As fault currents to earth are usually limited in magnitude by an earthing resistance, it is rather in regard to faults between lines that difficulties are encountered in securing immunity from operation on "through" currents. Mr. Wedmore, therefore, has proposed the use of a protective circuit responsive to earth faults and line faults separately.

Such a scheme would provide sensitive earth-fault settings, which are only affected by "through" earth faults limited by the earthing resistance, and for line faults less sensitive settings, which may be insufficiently sensitive to trip on "through" faults. No useful purpose is served by sensitive line-fault settings, because faults of this nature necessarily involve heavy currents.

Mr. Wedmore's proposed arrangement is shown in Fig. 24, and it will be seen that the protective transformer consists of two portions—a closed ring embracing all three primary conductors, and inside the ring a star-shaped member.

Primary line currents will not cause saturation of the ring core. By the term "line currents" it is intended to convey that the vector resultant of the currents in all the phases is zero, i.e. no leakage component is present.

On the occurrence of an earth fault fed through a single transformer of this nature, there will immediately be a vector resultant other than zero, due to which the ring core will become magnetized. The star-shaped member, on the other hand, will become magnetized by line currents. As has been pointed out, no particular purpose is served by the provision of particularly sensitive line-fault settings, and, accordingly, the Y-shaped core is built of such a size that air-gaps are presented between its extremities and the surrounding ring. The ring core, therefore, will not become saturated under normal-load conditions. The arrangement will afford a measure of protection comparable, so far as line faults are concerned, with the earlier air-gap types of opposed-voltage protective transformers. Owing to the closed ring core, however, a very much greater sensitivity in regard to protection from earth faults will be achieved without resorting to the use of a specially sensitive relay.

By the provision of similar transformers at each end of the protected cable, connections for opposition of voltage being made by a pilot cable, discriminating protection as regards the circuit embraced may be obtained. In order, however, that there shall be no increase in the conventional number of pilot conductors, Mr. Wedmore arranges windings as shown in Fig. 24. So far there are two separate protective windings, and by connecting these to a common con-

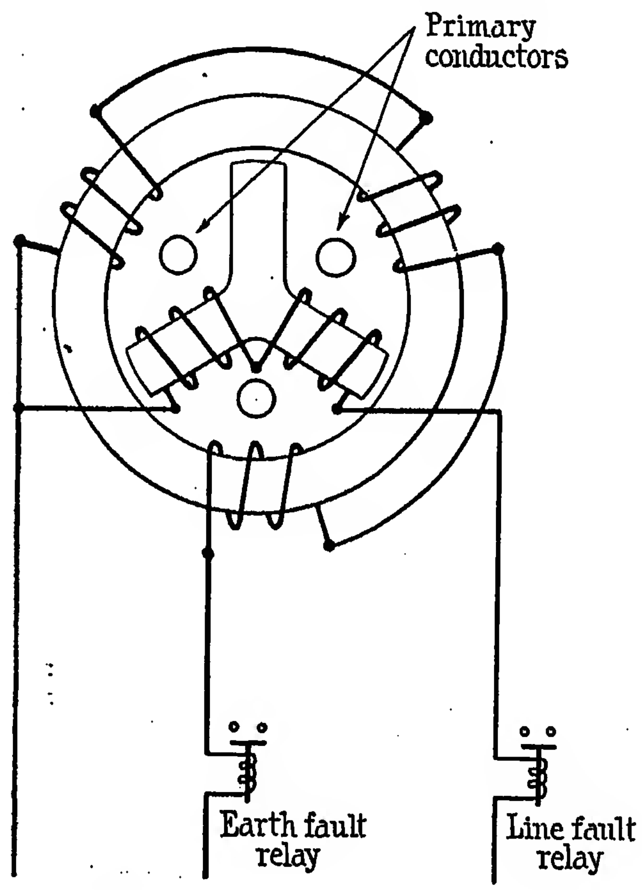

FIG. 24.—Diagram of protective transformer for line- and earth-fault protection.

ductor it is possible for the complete scheme to function when connected by a three-core pilot cable. It should be noted, however, that the line sensitivity will vary according to whether the line fault embraces both or one only of the wound limbs, this characteristic being inherent to this form of apparatus. Since, however, on the occurrence of a line fault heavy currents are immediately set up, the actual value of sensitivity is of small import. It will be seen that the earth relay in this scheme can only be affected by capacity currents flowing in the pilot cable to the extent of "through" earth faults, and these, due to the earthing resistance, will be of limited magnitude. The earth relay, however, will not receive in its operating winding any capacity currents set up by line faults. Moreover, since the ring core remains unmagnetized on the occurrence of line faults, it is clear that no very great balancing difficulty is likely to be encountered

so far as the earth relay is concerned. As regards the line relay, the question of balance is not of great importance, as only relatively high fault settings are required.

The author feels that the arrangement due to Mr. Wedmore is capable of notably better results than any by requirements connected with phase separation. It is essential in the arrangement illustrated in Fig. 24, for instance, that all phases should be brought through one special transformer. A suggestion has been made that this transformer should be situated in a special form of trifurcating box. Faults are not unknown in

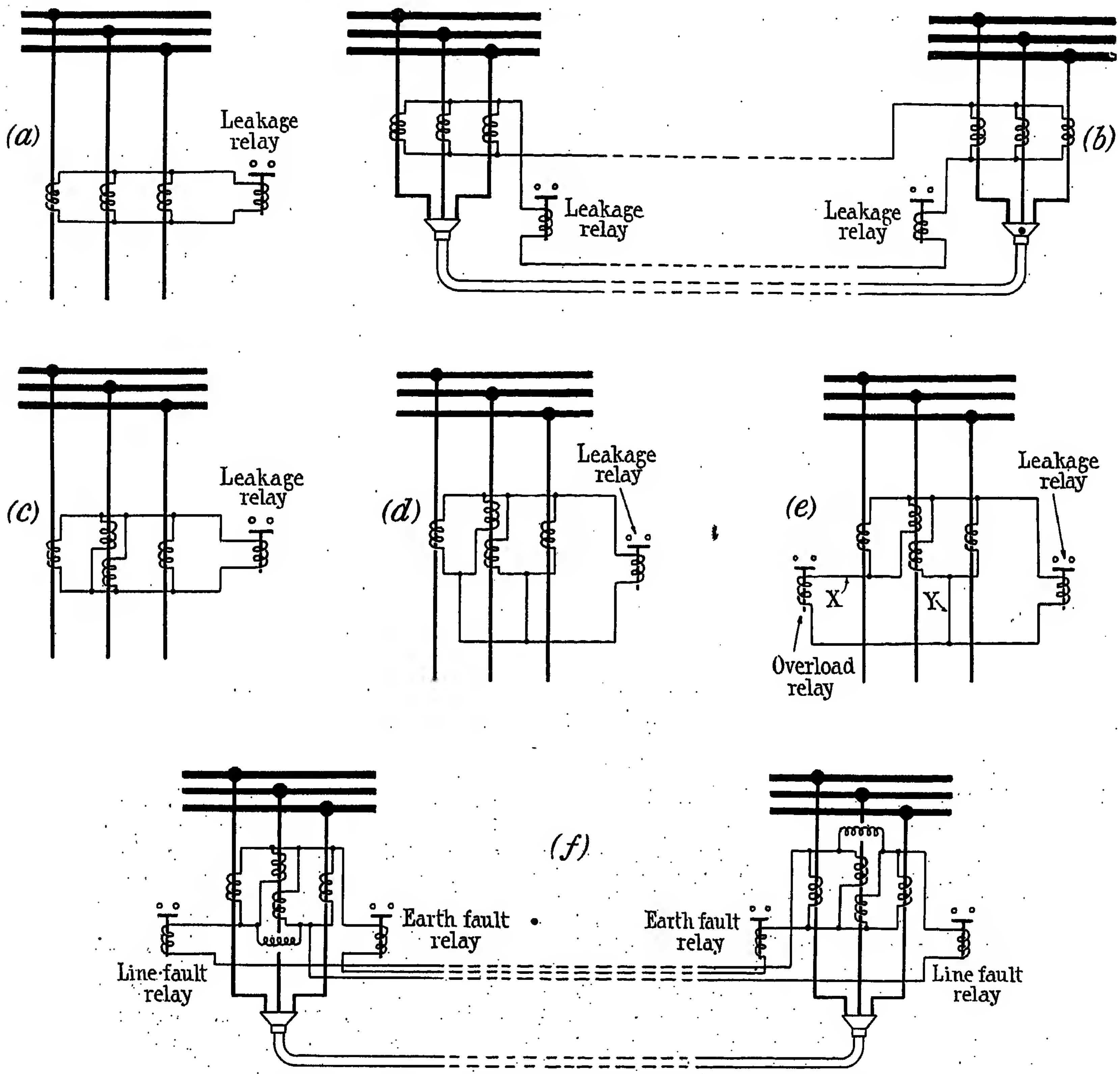

FIG. 25.—Evolution of protective circuit for line- and earth-fault protection.

previous system of opposed-voltage feeder protection, this being more particularly due to the principle enunciated by Mr. Wedmore regarding discrimination between line faults and earth faults.

In a number of the protective schemes which it is proposed to describe, use has been made of this principle. For the protection of feeders by a pilot-wire system, however, the author has been influenced joint boxes, however, and the author was directed by the British Thomson-Houston Co. to devise, if possible, means of providing the advantages inherent in Mr. Wedmore's scheme, at the same time retaining conventional construction, so that current transformers of ordinary type could be used on the system. The evolution of this circuit through various stages is shown in Fig. 25.

Figs. 25 (*a*) and 25 (*b*) are self-explanatory. In Fig. 25 (*c*) two transformers having double the ratio are substituted for the middle transformer in Fig. 25 (*a*). This gives rise to no change in the operating characteristics, nor does the slight alteration indicative of the evolution of the scheme shown in Fig. 25 (*d*).

In Fig. 25 (*e*) a further relay, which carries a current proportional to the load, is added. Under all conditions, not involving leakage, the secondary currents in leads X and Y will be equivalent.

The other relay, as before, is responsive to leakage currents only.

The final step is shown in Fig. 25 (*f*), which represents a discriminating opposed-voltage circuit based on Fig. 25 (*e*). The points X and Y are now joined by a small resistance or reactance. If this were zero the conditions would revert to those of Fig. 25 (*b*) and the line-fault relay would be inoperative. An impedance, however, sufficient to provide a line-fault setting of a few hundred amperes is such as to allow under normal present characteristics similar to those of a symmetrical network of condensers, as shown in the diagram, except that the capacity will be distributed.

It is found that under all load- or line-current effects, irrespective of whether the currents in the three phases are symmetrical, there will be set up at each end of the pilot cable a voltage between the outer pilot conductors, the centre line being at an equivalent potential displacement from each of the outer lines. The middle conductor, in effect, forms a mid-point, and only when leakage currents flow is this condition upset. Consideration of the capacity network will show that capacity currents due to "through" line faults will not be set up in the pilot conductor in which the earth-fault relay is connected. These capacity currents are confined to the outer conductors. Capacity currents in the earth relays can only be caused by "through" earth faults, which in general are of limited magnitude.

So far as construction is concerned, the apparatus presents features exactly in accordance with con-

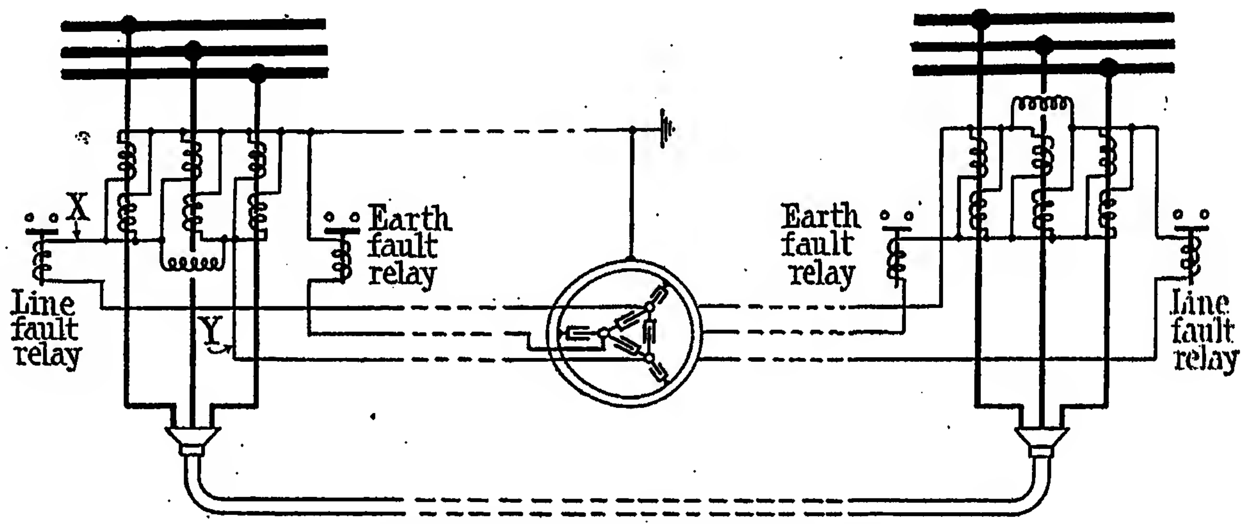

Fig. 26.—Effect of pilot-line capacity.

load conditions a free circulation of current between the current transformers. Thus saturation due to load currents does not occur and transformers having closed iron magnetic circuits may be used. Earth-fault currents, however, directly magnetize the transformer on the phase affected. Thus the arrangement is closely analogous to Mr. Wedmore's scheme, so far as operation in regard to faults is concerned. It is capable of providing separate line-fault and earth-fault trips, the latter being more sensitive than the former.

Due to the possibility of using ring-type transformers, it is not necessary, as in other opposed-voltage systems, to employ exceptionally sensitive relays in order to get good fault settings. Moreover, it is not essential that dissimilar types of transformer, as shown in the explanatory diagrams, should be used.

Three transformers, all exactly like the middle one, might be used without detriment to the results obtained. The windings would be put in parallel if they were installed on the outer phases.

This arrangement is shown in Fig. 26, which refers to the effects of capacity currents under "through" fault conditions. The pilot cable will be expected to ventional current-transformer design, the two cores being assembled together on a single porcelain insulator, and only differing from an ordinary current transformer in appearance, due to the fact that there are four secondary terminals instead of two. Only one type of transformer will now be required, and a replacement may be made on any phase, the secondary connection being arranged accordingly.

If this latter circuit be compared with Mr. Wedmore's arrangement, it will be seen to possess almost identical characteristics, at the same time permitting ordinary constructional methods to be employed; such transformers, moreover, if installed according to ordinary cellular methods of power house design, will embrace trifurcating boxes and all conductors right up to the actual oil switch, near to which it is usual to place a protective transformer.

This system will be inferior to the arrangement shown in Fig. 24 in one respect only, namely the question of current-transformer balance. This, however, may easily be overcome by the use of biasing transformers applied to the circuit, according to Fig. 23. The line-fault relay may on a "through" short-circuit

carry current due to out-of-balance and to capacity. It should therefore be subject to overload restraint under these conditions. The earth-fault relay may suffer from bad balancing under the same circumstances and should receive a similar restraint. It will also receive capacity current on a "through" earth fault, and accordingly should be restrained against such conditions.

The reactance shown in Fig. 25 (*f*) carries a current proportional to the "through" line current, and may therefore be replaced by the line-fault restraining windings. No P.D. will exist between the mid-point of the above restraining windings and the middle pilot conductor under any condition of "through" line current. A winding connected between this mid-point

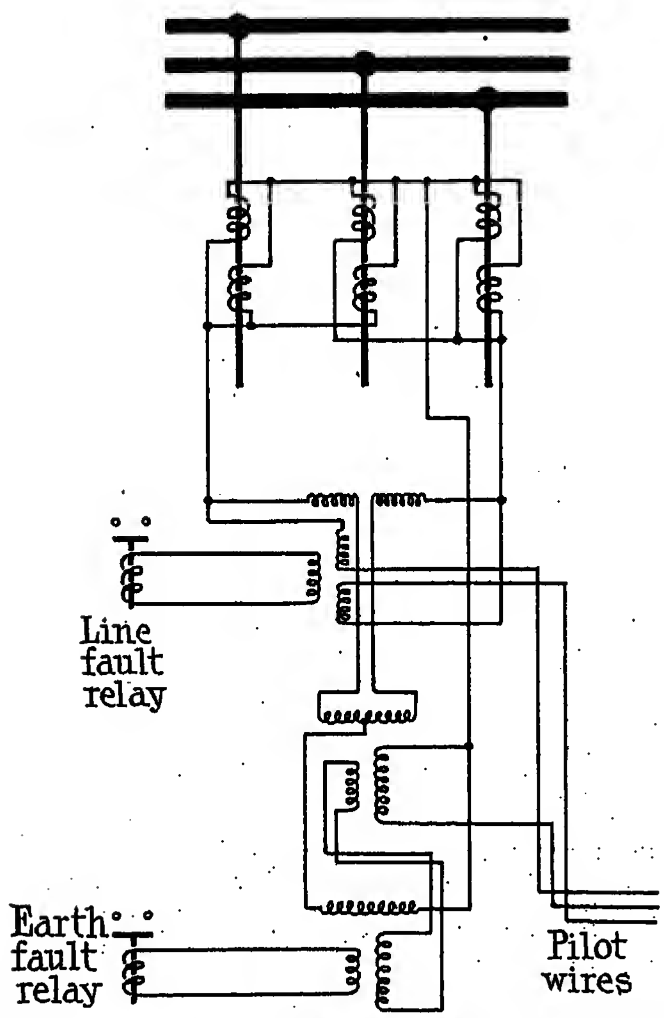

FIG. 27.—Diagram of opposed-voltage circuit with biasing transformers.

and the pilot conductor will receive current only when an earth-fault current is present in the primary circuit. The restraining winding on the earth-fault relay which is to be operative on "through" earth faults should evidently be thus connected.

In the complete scheme, therefore, which is illustrated in Fig. 27, the earth-fault restraining winding is connected between the neutral pilot conductor and the mid-point of the line-fault restraining windings, which are accordingly arranged so as to permit this. Both the line-fault restraining windings will have air-gap characteristics, as their effect is required only under heavy-current conditions. The restraint applied to the earth relay on the occasion of a "through" earth fault may, if desired, be arranged to become effective on small "through" earth faults, since the existence of the same is an abnormality. In the case of cables operating at pressures greater than about 11 000 volts the following effect may be of importance. The normal charging current of a cable, being the difference between input and output current, appears in the protective circuit as a fault current, and will not affect the earth relay, as it will contain no earth or leakage component. This capacity current in the primary conductors must not, however, be overlooked in regard to earth faults. If the cable protected be of considerable length there may be a charging current appearing as an earth fault due to the disturbance

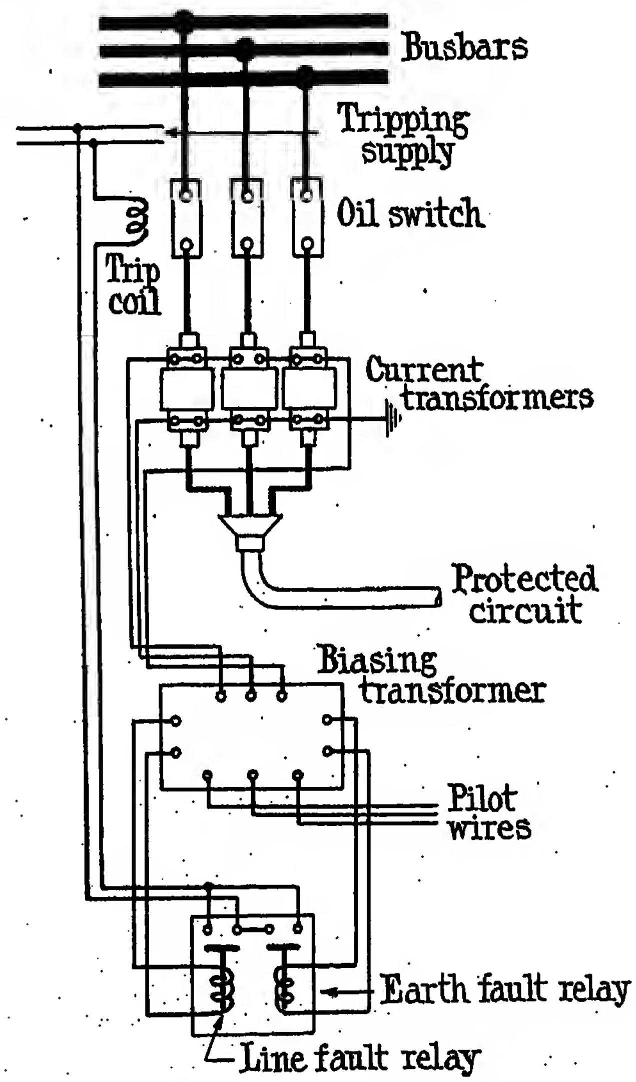

FIG. 28.—Wiring diagram of opposed-voltage circuit.

of pressure distribution on the power system. The wiring diagram is shown in Fig. 28.

As indicated above, the system described is specially adapted to give advantageous operation on power systems in which the maximum possible current that may flow to earth is definitely limited, and where the design is carried out with this application in view it is found possible, using bar-primary current transformers, to provide fault settings of between 25 and 50 amperes on faults to earth, using a plain relay capable of operating at 0·5 volt-ampere.

The principle which has been adopted, namely, that of discriminating between line and earth faults, and of assuming the latter to be of limited magnitude, has

been criticized on the grounds that it is not applicable in certain instances. It may be demonstrated that in the event of two simultaneous earth faults occurring on different parts of the network, and not on the same phase, a fault between lines that is not limited by the neutral earthing resistance will result. It is not impossible for this to be fed through two different feeders in such a manner that the current will appear in each as a " through " earth fault of the magnitude actually attained by the between-phase short-circuit which, in fact, exists. Tests on the gear, however, indicate that in a large number of practical cases the fault settings given above may be maintained with satisfactory results, even if this somewhat exceptional condition be envisaged.

Circulating-current feeder protection.—This system is an extension of the methods which have been described in connection with the protection of generators and transformers on the circulating-current system. It would be needed. These, however, make the system too expensive.

The connections will, therefore, be made in accordance with Fig. 29. It will be seen that whilst the occurrence of a fault on the length of cable embraced by the protective circuit will evidently cause the relays to trip, currents of sufficient magnitude fed through the system will set up out-of-balance currents in the operating windings due to the pilot-wire resistance. To the extent, therefore, that these further effects exceed transformer unbalance they must be regarded as additional discrepancies necessitating biased characteristics, and it is due to these considerations that the present system of feeder protection has been found to be useful only where such features have been provided. The arrangement in Fig. 29 may easily be rendered immune from incorrect operation by the provision of suitably designed biasing transformers.

Whilst the above arrangement will function correctly

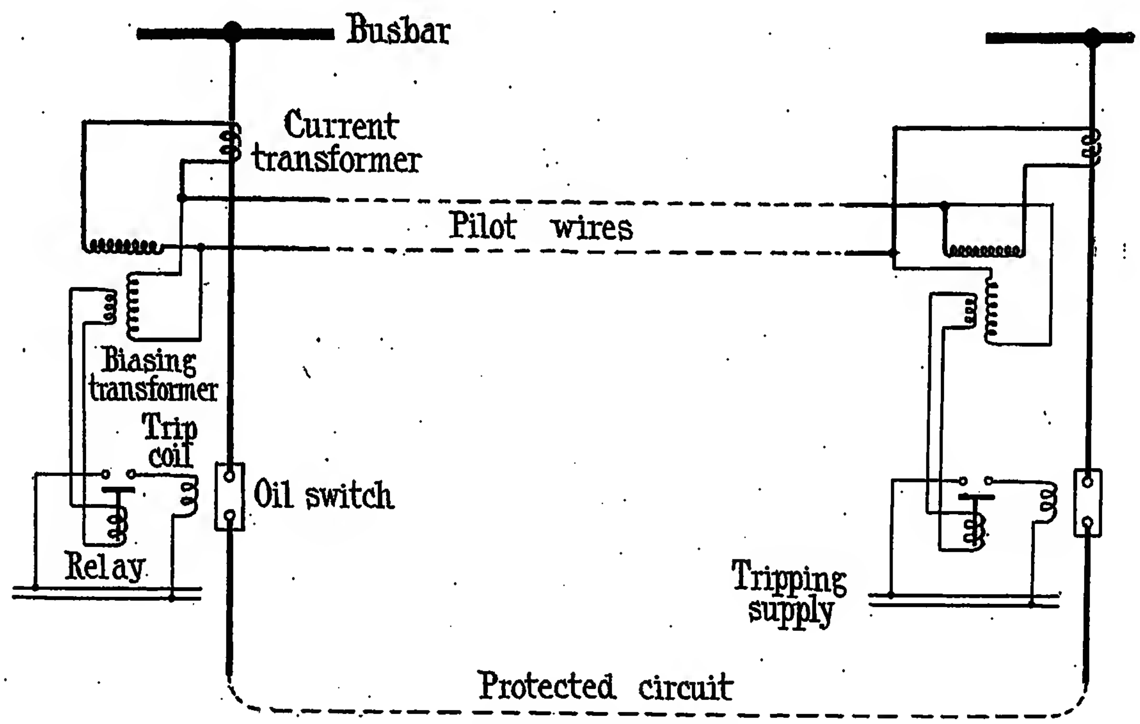

FIG. 29.—Circulating-current feeder protection.

differs from these schemes in the arrangement of its circuits, on account of the additional difficulties incidental to the greater lengths of pilot line connecting the protective transformers. These difficulties are entirely associated with the fact that a pilot cable used in conjunction with a feeder protective system may be expected to have a resistance very considerably in excess of the figure which might be met with in systems of protection having no secondary connections extending outside the station in which the protected plant is installed. Moreover, it will always be possible, in a small circulating-current circuit confined to one station, to make precisely equipotential points accessible for the connection of operating windings, etc. In the arrangement essential to a feeder protective scheme these equipotential points will be found at opposite ends of the line, and, for both operating windings to be connected between these points, additional pilot conductors under all conditions, it may be improved by a slight departure from the simple form shown. The alterations, as detailed below, will be more readily appreciated if consideration be directed toward certain conditions associated with the use of biased circuits in general.

Having, at some length, described the various ways in which a biasing action may be simply achieved, and restraining effects of very considerable magnitude provided, by the biasing transformer, the author wishes to deprecate any impression which may have been created to the effect that a complete remedy for out-of-balance effects of any extent resides in the biasing principle, and that there is no object in making any attempt to provide transformers or circuits which balance to a reasonable economical extent.

It should be noted that an out-of-balance effect due to any cause would be expected to produce in the operating

windings of any differential protective circuit, currents proportional to the transmitted load, when the feeder or plant protected is sound. If the balance be so bad that these currents reach an appreciable magnitude under normal conditions of load, it will be obvious that, should the gear be called upon to clear a fault under such circumstances, the sensitivity will be augmented or decreased according to the relative direction of the respective currents. Clearly, therefore, unlimited imperfection of balance might be very detrimental to the proper functioning of differential protective gear, even though the biasing effect may be sufficient to prevent the relays being tripped by the heaviest of "through" faults.

It will have been noticed in the arrangement shown in Fig. 29 that the unbalancing due to resistance is proportional to the transmitted load, whereas it has been pointed out that the troubles associated with

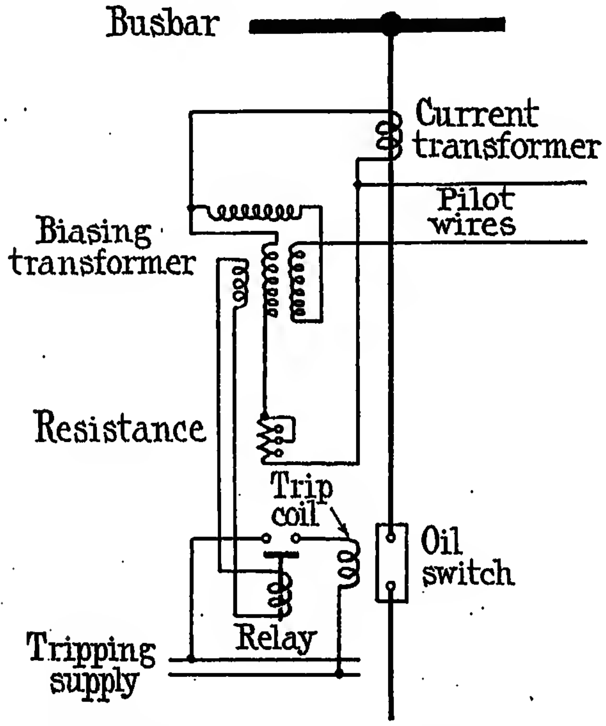

Fig. 30.—Improved form of circulating-current feeder protection.

transformers are not usually in evidence until very considerable overload currents are attained.

Whilst it is considered that the above scheme is capable of entirely satisfactory results in cases where the relation of the pilot cable resistance to that of the secondary turns, etc., is not exceptional, it is possible to utilize the arrangement shown in Fig. 30. In this the resistance effect may be balanced out, the biasing action being accordingly arranged to correspond to the usual extent of unbalancing where transformer effects only need to be taken into account.

It should be noted that it is not necessary to take any special measure to obtain exactly correct duplicate resistances. Provided that these are approximately as required, no special adjustments, after installation for instance, should be entailed. If the balancing effect of the duplicate resistance be sufficiently close to avoid, at overloads of no great magnitude, the trouble described, the biasing action will preclude any incorrect operation due to more severe "through" faults.

The circulating-current feeder system described has not yet been commercially developed, but the author believes it to be capable of very good performance.

Split-conductor protection.—The balancing difficulties

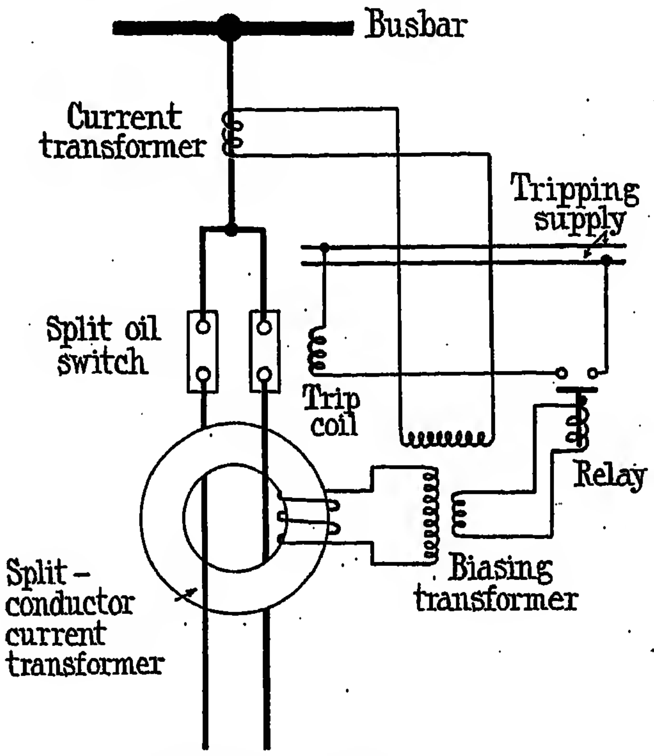

Fig. 31.—Application of biasing transformer to split-conductor circuit.

associated with this system are mainly connected with cable jointing so as to obtain exactly equal impedance in both splits. When the reactance type of protective transformer is used, exceptional balance, both of the

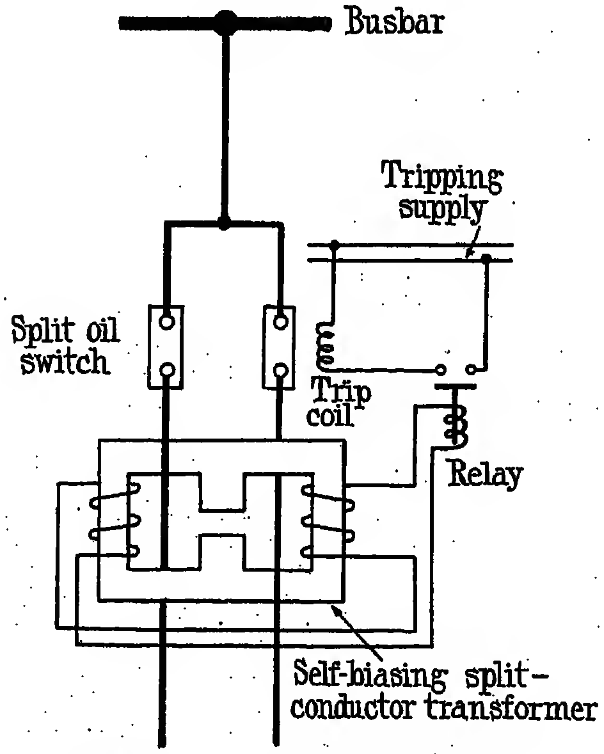

Fig. 32.—Self-biasing split-conductor transformer.

cable and of the transformer itself, is necessary. All the diagrams are applicable to both simple and reactance forms, but the former is illustrated.

An obvious method of providing a biased form of split-conductor protection is shown in Fig. 31. This

is of interest in that existing gear might be modified very simply on these lines should this be found desirable.

The biasing feature, however, may be incorporated in the split-conductor transformer as shown in Fig. 32. The external connections would then be similar to the ordinary arrangement having no biasing action (see Fig. 33).

If Fig. 32 be compared with Fig. 1 (*c*) it will be seen that equivalent currents in the two splits produce excitation corresponding to a restraining winding, whereas difference currents function as an operating winding and energize the relay.

An even better scheme, particularly suitable for e.h.t. application, is shown in Fig. 34. Ring-type cores are used throughout, as these are the kind most easily insulated for high pressures. A simple differential

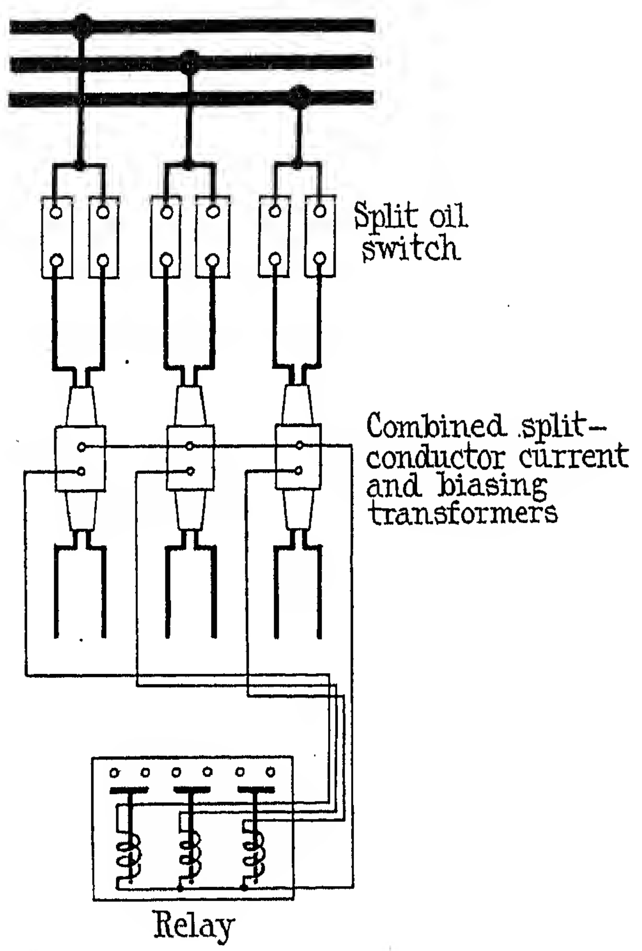

FIG. 33.—Wiring diagram of split-conductor system.

core only excited by a fault current, exactly as in the ordinary arrangement, is here used. The secondary of this core excites the relay through the medium of a biasing transformer of the type consisting of a pair of rings, as illustrated in Fig. 1 (*a*). The operating excitation sets up fluxes in the rings in opposite directions, while the primary windings passing through the biasing cores magnetize them in the same sense. Thus they have no inductive effect on the relay, and on heavy overloads they will act as restraining windings. Fig. 35 shows how such a transformer might be constructed, the biasing cores being arranged on each side of the differential core. The ring-core scheme does not lend itself to the provision of an air-gap to reduce the restraint under normal load conditions. This characteristic is hardly necessary in split-conductor work, as no very great extent of maximum restraint is required, and such proportion of this as may be present on normal load will not seriously affect the sensitivity. The air-gap effect may be obtained, however, if required, as follows: A further winding is provided on both the biasing cores, the two forming a closed circuit. This is not inductively related to the operating or secondary windings but is wound so as to receive current induced by the primary or restraining current. It may be arranged to have such a resistance as will prevent saturation of the cores at light loads but permit of this when the "through" current is of greater magnitude. This winding could be used to operate an overload relay.

PARALLEL-FEEDER PROTECTIVE SYSTEMS.

General.—Purely differential systems of parallel-feeder protection are entirely dependent for their

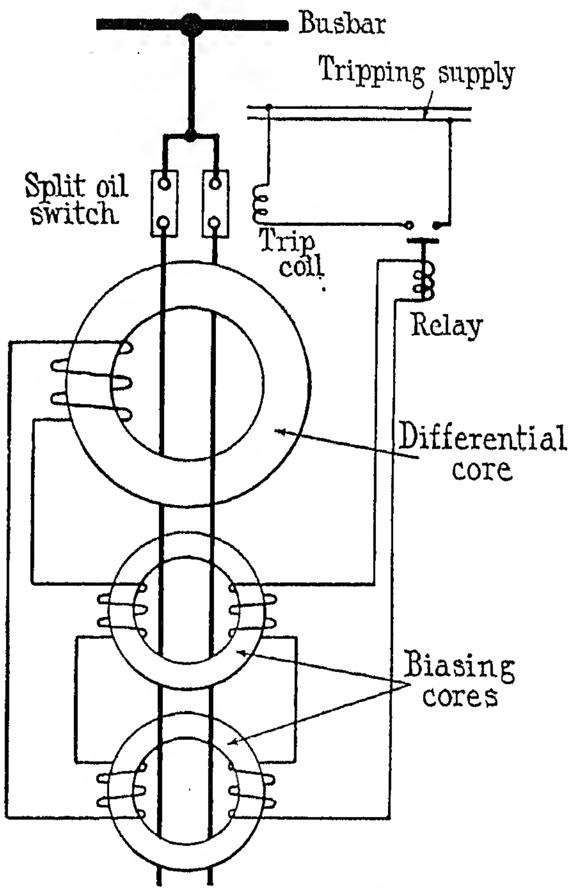

FIG. 34.—Diagram of self-biasing split-conductor transformer with ring cores.

functioning on the installation of a number of feeders operating in parallel under all circumstances.

In comparison with the split-conductor system these arrangements present the advantage that if there is a fault on one line, the supply may be maintained through the remaining feeder or feeders.

The protective relays on sound lines must be immune from disturbance due, first, to faults on other portions of the power system, and secondly, to a breakdown on one of the lines in the group protected. Overload restraint will be desirable on the former, whilst the latter condition will be met by arrangements of biasing transformers operating on the discriminating or directional principle. The particular problems met with in systems of the present form are due to the use of two separate protective circuits at each end of the lines.

These give rise to two conditions under which the apparatus must discriminate correctly: first, when both ends are completely closed up, and secondly, when one end of the faulty line has opened. In the latter instance the transmitted load will cease to be divided correctly among the parallel feeders. The circumstances are such that either end may open first, depending on the location of the fault.

these lines, however, is open at the other end and, unless this circumstance be allowed for, incorrect operation on faults and needless disturbance under healthy conditions may result.

Balanced-current system.—This system operates in accordance with the principles described in relation to Figs. 8 and 9, and in its simplest form would consist of a three-phase circuit, as shown in these figures.

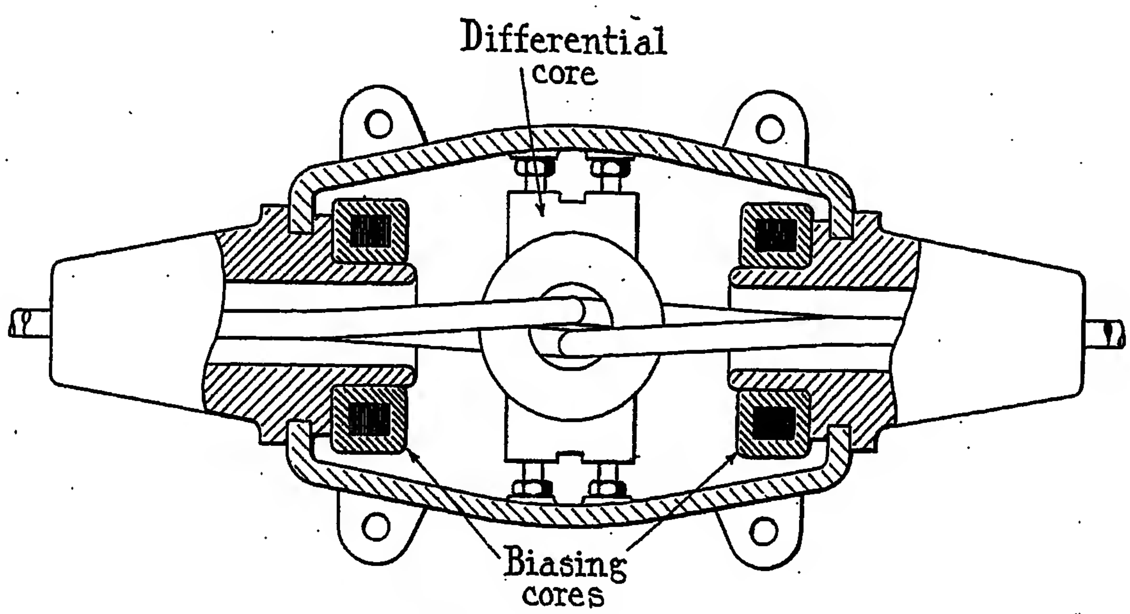

FIG. 35.—Construction of self-biasing ring-core split-conductor transformer.

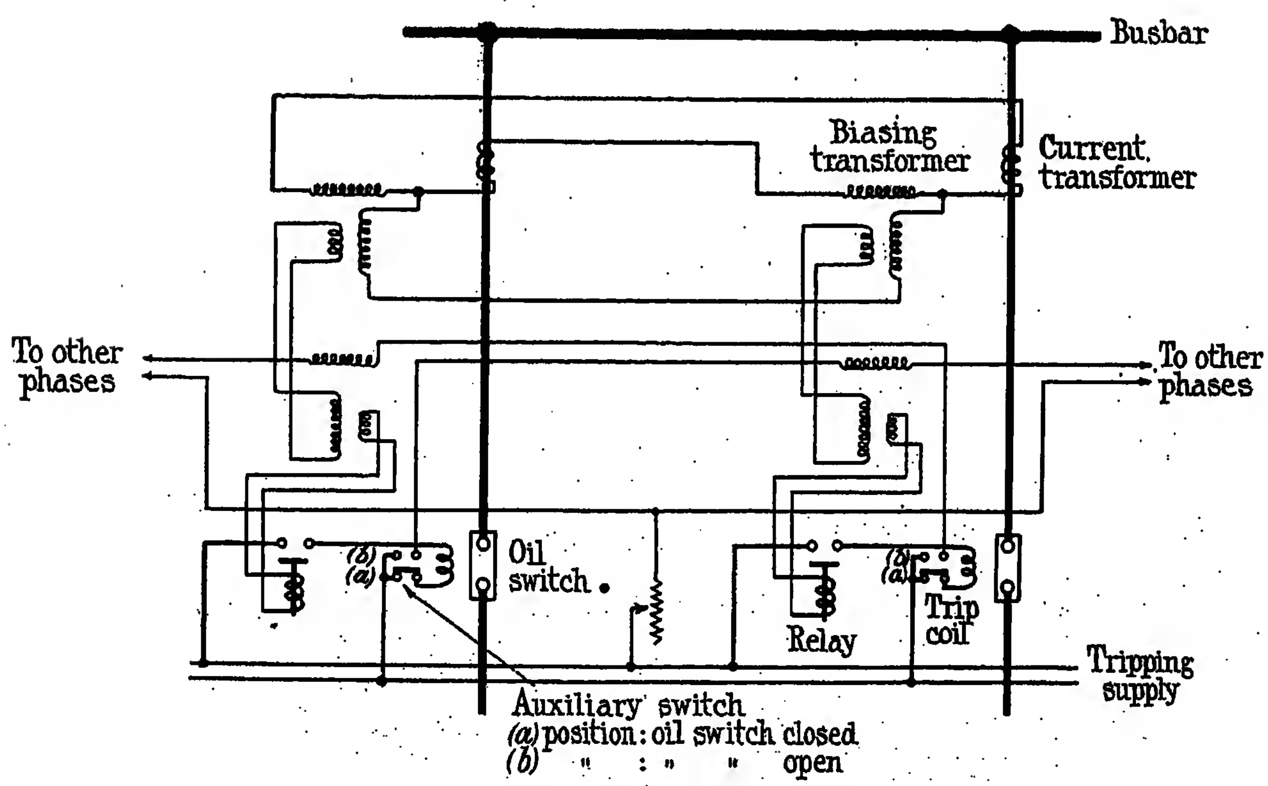

FIG. 36.—Balanced-current protective circuit.

It is evident that the protective circuit may be automatically modified by auxiliary switches at the end where the line is not closed up. It is the conditions obtaining at the remote end which must be examined if such protective gear is to be immune from disturbance due to switching operations involved by the normal functioning of the supply system. Here the protective circuit will be completely disposed for discriminating between parallel lines completely closed up. One of

If a fault causes one feeder switch to open, the complete apparatus appropriate to both lines is automatically rendered inoperative. Clearly no discriminating function can be provided when only one cable remains in circuit, and if no change be made to the protective circuit when one line is open, the second line will trip when the current carried by it is equivalent to the fault setting of the protective gear. Various methods are available by which this end may be attained, an

obvious solution involving triple-pole auxiliary switches adapted to short-circuit the operating windings.

Two preferable arrangements will now be described. If it is desired to cut out entirely the discriminating gear, and to rely on such stand-by overload or other apparatus as may exist, then both relays may be subject to a direct-current restraint if one feeder is tripped. This necessitates only a single-pole auxiliary switch for each three-phase line. The extent of this restraint would be such that no possible value of current could effect tripping.

In certain instances, however, no additional protective means may be present, and it may be an added advantage to provide for a measure of protection transformer circuits or in relay connections, with the exception of the conventional practice of opening the tripping circuit on the circuit breaker instead of at the relay contacts.

The simple three-phase circuit hitherto described, whilst it is capable of entirely satisfactory and correct operation within its sphere of application, is subject to certain restrictions. If these be now indicated the advantages of the improved arrangement will be more clearly understood.

Operating conditions of balanced-current gear.—It has been shown that if one feeder be opened there will be a tendency for the remaining line to be automatically tripped unless means of the nature described be applied

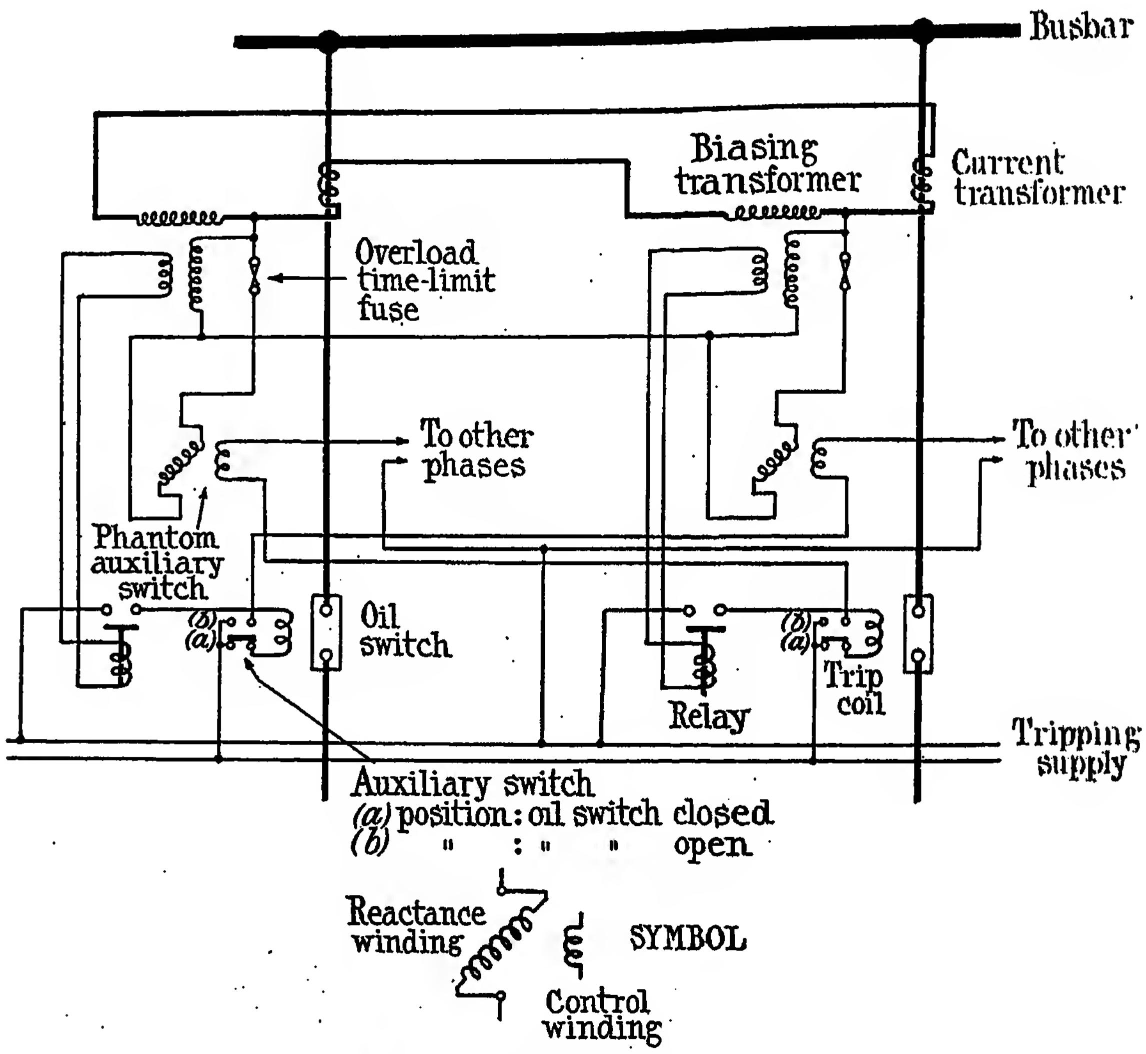

FIG. 37.—Balanced-current circuit with stand-by protection for single line.

(not, of course, of a discriminating nature) by the balanced-current gear. Such an arrangement is given in Fig. 36. On either feeder coming out of service a restraint is applied to the relays associated with the remaining line. The magnitude of this restraint can be controlled by a resistance, or designed for a constant value, such that a heavy overload or short-circuit will operate the relay. As an alternative, fuses or other time-lag devices can be connected in parallel with the operating windings in series with phantom switches so that the overload protection provided on the single remaining line shall not be instantaneous. This scheme is shown in Fig. 37. Attention is particularly directed to the fact that in both the latter arrangements no switching is carried out in current-

in order to preclude the possibility of such action. Clearly this must occur with apparatus devised for tripping the line carrying the greater current, since one feeder will carry the total transmitted load whereas the current in the other will be zero.

The inconvenience of this effect may perhaps be more evident if it be pointed out that when a double feeder equipped as above is carrying normal load, the inadvertent opening of a switch at the far end may cause complete interruption of the supply unless the fault setting be definitely in excess of the maximum load corresponding to the rating of both lines. Unless this latter condition be complied with it will be found that, in general, not only will incorrect operation be possible on the occurrence of faults of an order of

magnitude comparable with load current, but that tripping of the protective gear will take place if the switchgear be operated by hand, according to the normal exigencies of service. Consider an earth fault occurring on a feeder in such a position that initial operation occurs at the end remote from that at which the gear in question is installed. If the pair of lines be carrying currents of the order of their rated load, the sound feeder may be overloaded when the switch at the far end opens. Evidently the faulty line can only be cleared when the earth fault exceeds in magnitude the current in the sound cable, and moreover, if the resistance of the fault be such as appreciably to limit the current, the sound line may come out, thus resulting in a complete shut-down.

difficulties may be entirely obviated in a simple manner by designing the apparatus on the lines already indicated in connection with the opposed-voltage circuit, earth faults and line faults being dealt with separately.

Very successful results have been realized by parallel-feeder systems operated on the balanced-leakage principle, the method of application of the biasing transformer to such schemes being seen in Fig. 9. In forms of this system requiring transformers which entirely surround the three cores of a cable, the connections would, in fact, be practically identical with those in this diagram.

Where ordinary current transformers are used the arrangement, which possesses the following properties, is as in Fig. 38. Only currents of which the vectorial resultant is other than zero will excite any of the biasing transformer windings. All load or other currents not of this nature will circulate in the current transformer secondaries only. If either feeder carry an earth or leakage current greater than that in the other, a corresponding difference current will appear in the operating windings of the biasing transformers, and tripping will occur on the relay corresponding to the feeder carrying the greater leakage current, as indicated in Fig. 9. In the event of an earth fault being present on some portion of the supply system beyond the protected feeders, this will appear in equal proportion in both of the lines and will accordingly give rise to a circulating current in the restraining windings. Thus, even though the fault is not exactly equally shared, due to variations in feeder impedance, the relays cannot trip.

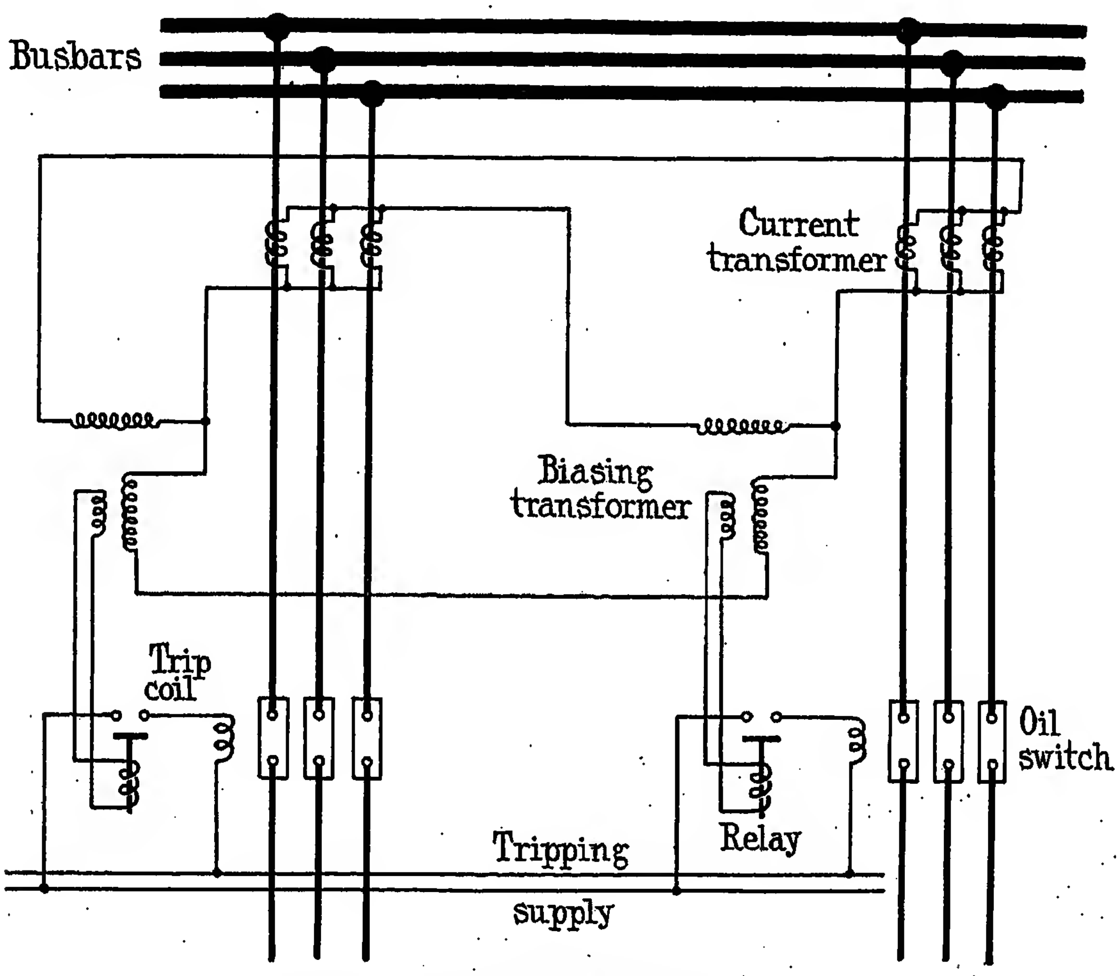

FIG. 38.—Balanced-leakage protective circuit.

With regard to the latter point, it is impracticable to close up the feeders at all under conditions involving appreciable load, except in special sequence or unless the protective gear be first rendered inoperative by hand switches or other means. The normal connections can only be restored when all switches have been duly closed.

It is felt that protective gear in general cannot be recommended if it in any way adds to the switching operations involved in normal service, or if restrictions are introduced by its use. Moreover, the use of such hand switches is further to be deprecated on account of the possibility of closing a switch on to a fault.

The arrangements above described should, therefore, be limited to insulated systems or to those on which the neutral is solidly earthed.

Improved form of balanced-current circuit.—The above

Fig. 38 shows the simplest possible form of this arrangement, while Fig. 39 shows an improved scheme capable of superior results. By providing an overload restraint in this manner it is possible to get even more additional protection is obtained against all forms of line fault. The complete circuit is indicated in Fig. 40, and it will be noticed that the connections providing protection from line faults correspond to those in

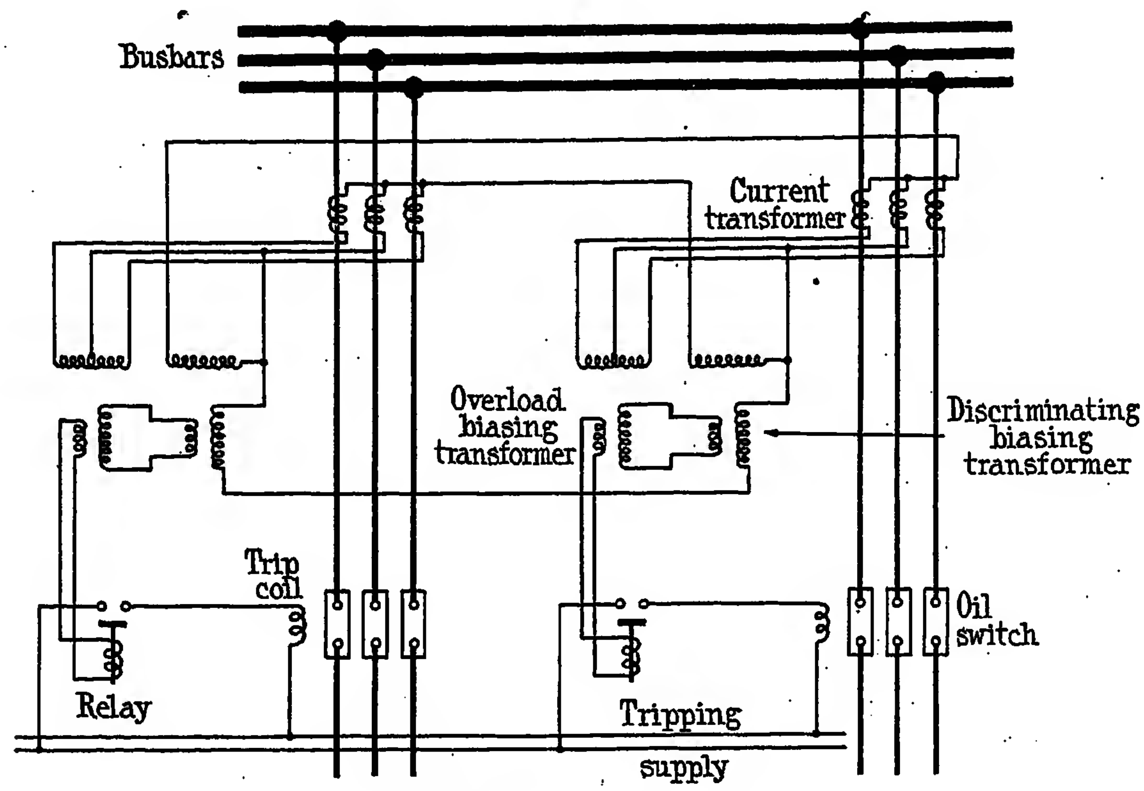

FIG. 39.—Balanced leakage with overload restraint.

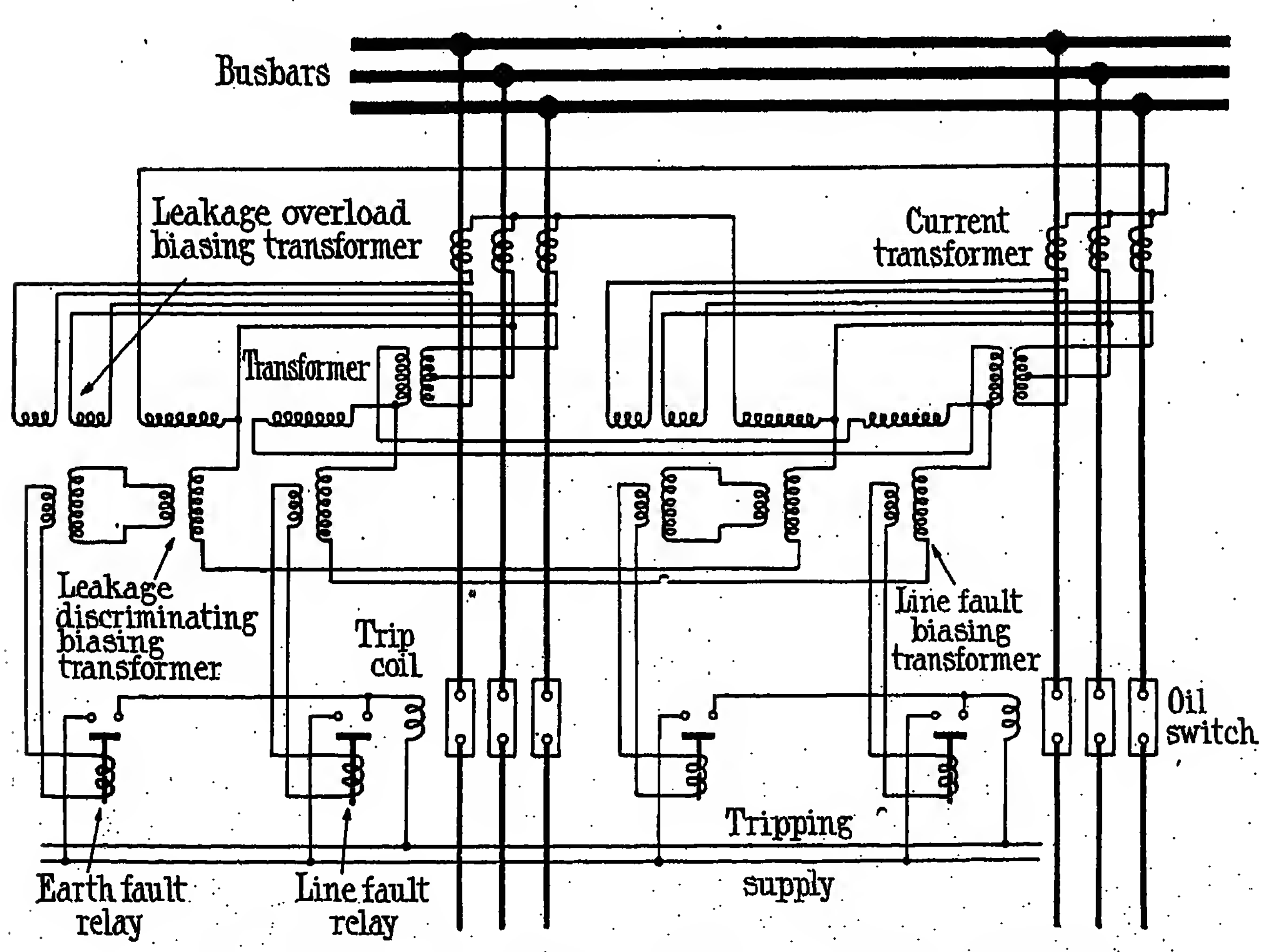

FIG. 40.—Balanced-current circuit for earth- and line-fault protection.

sensitive operation, complete general immunity being at the same time provided. By the provision of a small current transformer, together with a further discriminating biasing transformer energized from this, Fig. 9 if the secondary of the transformer, which is excited by such faults in Fig. 40, be considered to represent the current-transformer windings in Fig. 9.

The following characteristics will be associated

with the final arrangement according to Fig. 40. (1) "Through" earth currents will set up a circulating current which will appear only in the restraining winding of the leakage discriminating biasing transformers. (2) "Through" line faults or overloads will excite the leakage overload restraining windings

In this diagram no provision is made for utilizing the apparatus for any further measures of protection in connection with the operation of a single feeder. On one line coming out of service the protective gear is rendered inoperative by short-circuiting the line-operating winding and opening the leakage-operating winding by

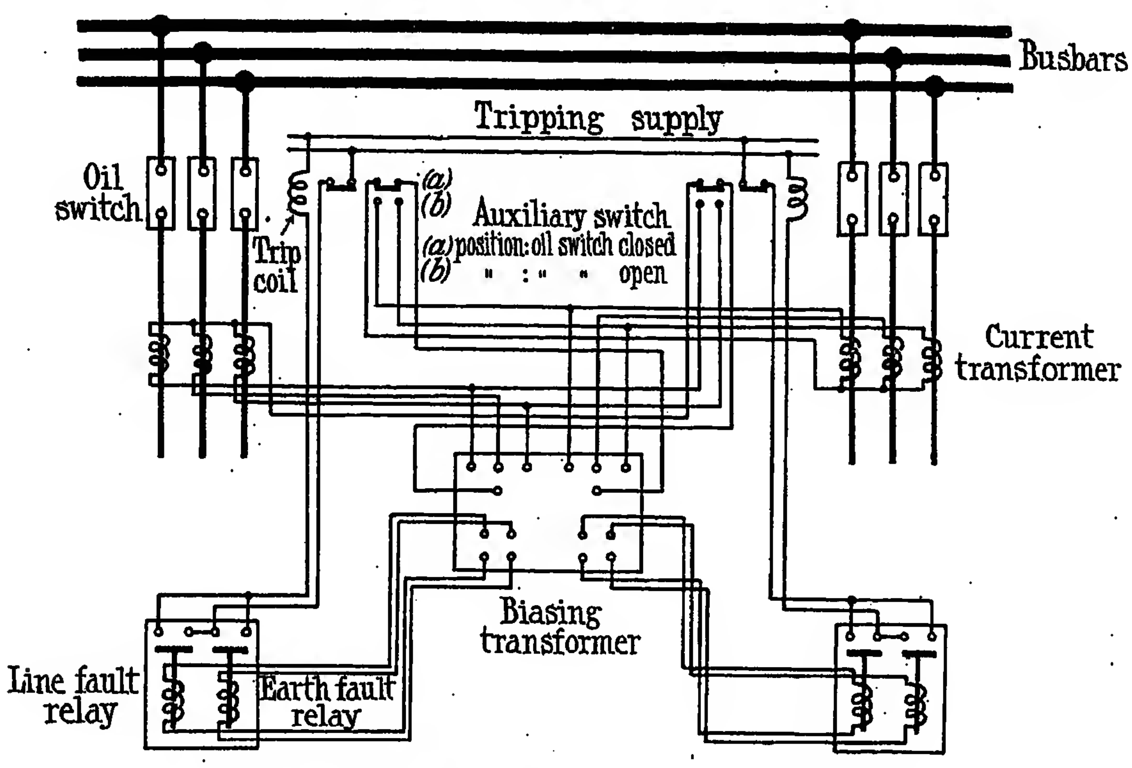

FIG. 41.—Wiring diagram of balanced-current system.

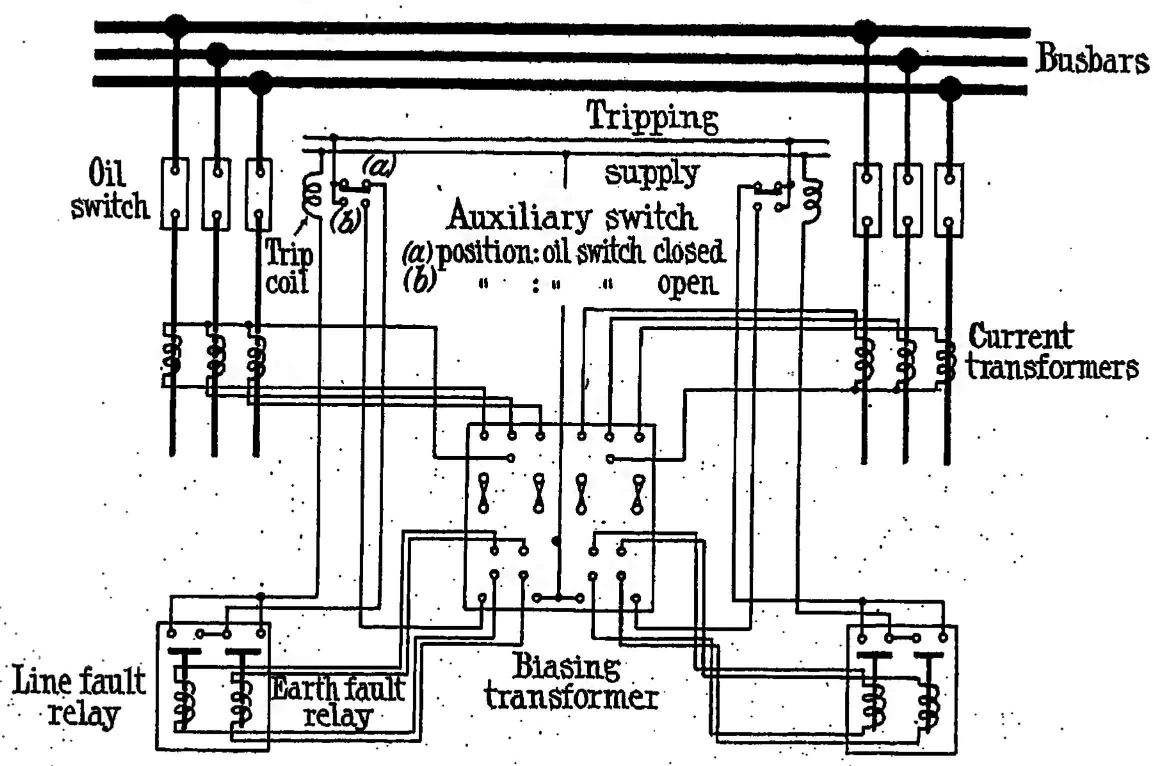

FIG. 42.—Wiring diagram of balanced-current system with stand-by protection for single line.

and also the restraining windings on the line-fault biasing transformer. (3) Earth faults on either feeder will operate the leakage relay on the defective line and will restrain that on the sound circuit. In a corresponding manner line faults will effect correct operation of the line-fault relays.

Fig. 41 shows the actual wiring diagram involved. It will be seen that no notable complications are added.

means of auxiliary switches. Evidently it is possible to avoid all contacts in the transformer and relay circuits by an arrangement similar to that given in Fig. 36.

Again, a scheme analogous to that shown in Fig. 37 may be provided. This scheme is given in Fig. 42. The remaining single line is, according to this arrangement, automatically protected from sustained short-

circuits or earths on any portion of the supply system to which it transmits energy. It is to be noted that should the leakage fuse be removed by hand subsequent to single-line operation having occurred, instantaneous leakage protection is achieved. Similar arrangements may be made for protecting multiple feeders.

Where the above systems of protection are applicable it is found that, using bar-primary current transformers of ordinary design and not exceeding 400 ampere-turns, operation of the protective gear may be effected on current differences equal to 20 per cent of the normal rating. In the case of earth faults, these figures may obviously be improved upon by the employment of special transformers. The corresponding figure in regard to line faults is recommended to be in the neighbourhood of 200 per cent of full load, but the apparatus may be provided or adjusted over a wide range in this respect.

It is particularly desired to direct attention toward the fact that, with the settings referred to, the presence of the apparatus may be entirely disregarded from the point of view of normal operation of the supply system, to exactly the same extent as obtains with pilot-wire systems for single lines.

Balanced-power system.

Operating conditions.—This system must be employed in any circumstances where, amongst a group of parallel feeders differentially protected, the occurrence of a fault cannot be depended upon to set up an excess current in the faulty line. These conditions are peculiarly associated with the receiving ends of parallel lines and they arise more particularly in connection with double feeders. Since, however, in the majority of instances in which three or more circuits are involved, it may be necessary from time to time to operate with but two lines in service, the employment of such gear is not restricted to the double-feeder case only.

The method of application of the biasing transformer may perhaps be more clearly indicated in relation to the more usual case of the protection of the receiving end of two parallel lines. The general conditions of operation of parallel feeders, as regards freedom from interference with normal functioning of the supply system, have been discussed above in connection with the balanced-current system. It has been shown that unless fault settings exceeding normal load currents be employed, the presence of the latter will cause unnecessary tripping of the protective gear under certain circumstances due to operation of the switchgear. These effects are less inconvenient when occurring on apparatus concerned with the protection of the receiving ends of parallel lines. The reason is that when switches are operated at the remote end the resultant unbalancing of the load currents is more likely to trip the line already opened than to cause interruption of the supply after the manner described in regard to the protection of generating ends. The use of fault settings of less than normal load, however, will prevent the feeders from being closed up except in the conventional order and may give rise to other troublesome effects. Under any conditions of emergency or abnormal working, petty hindrances in re-establishing supply, etc., are inclined to present exaggerated disadvantages.

It has been shown how such difficulties may be avoided by the separate treatment of line and earth faults, and it is now proposed to describe means of carrying into effect the same principle in connection with directionally functioning apparatus.

Fig. 43 shows a simple differential arrangement based on Fig. 11. It will be seen that the operating windings of each biasing transformer excited from

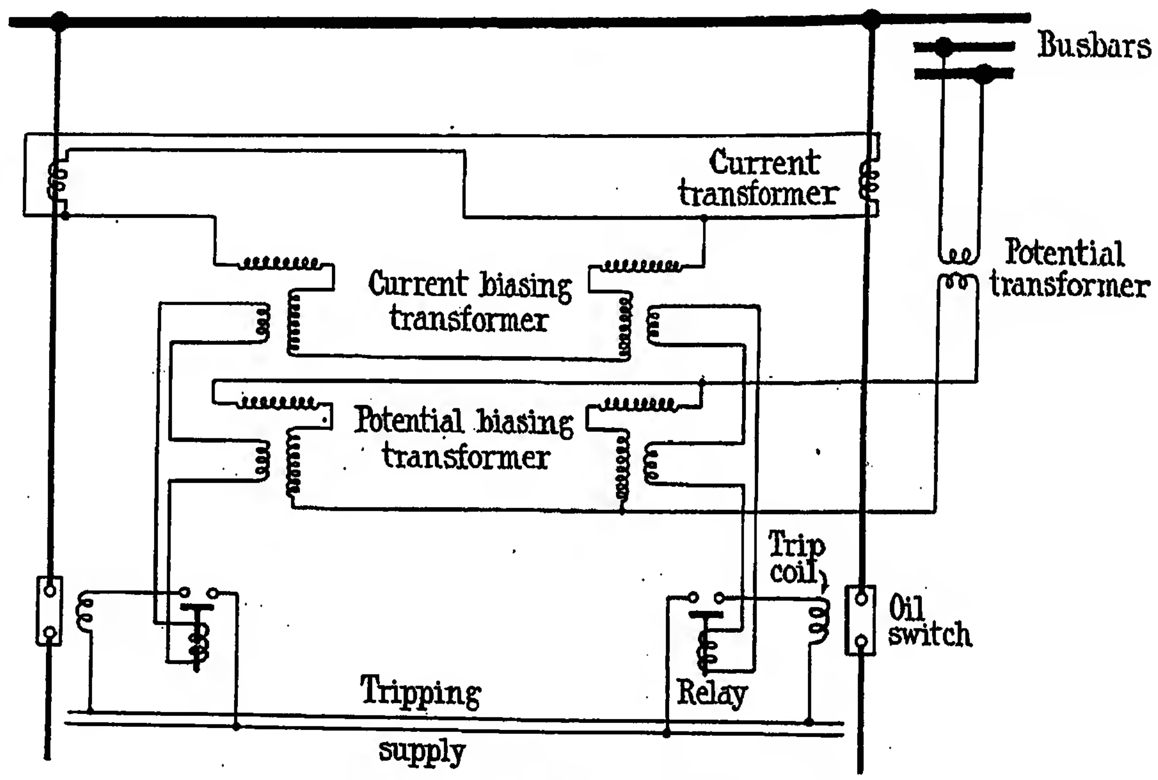

FIG. 43.—Simple balanced-power circuit.

current-transformer secondaries are connected between equipotential points in a circulating-current system according to the usual practice. In such an arrangement no current will be found in these operating windings unless a difference in magnitude or phase exists between the currents in the parallel conductors. If there is such a difference, due to a fault on one of the lines, one or other of the relays would be operated by the combined effect of the current and potential biasing transformers.

It may be stated generally that the operation of such differential directional circuits, whether installed at receiving or generating ends, will be somewhat as follows: The faulty feeder will be that which is receiving the largest amount of power flowing from the busbars into the feeders. Thus a faulty feeder will carry the greater current at the generating end but may carry the lesser current at a receiving end. The faulty feeder would be carrying a forward difference of power at a generating end and a reverse difference at a receiving end.

Such a protective circuit would, however, under all conditions operate at a fixed value of fault current and, having regard to the principles discussed in Section I and the systems of protection already described, it is doubtless superfluous to recapitulate the arguments in favour of biased circuits, i.e. those in which an overload restraint of such magnitude as will ensure adequate immunity from operation on heavy through faults is introduced, there being present the usual unbalancing in primary conductors and current transformers under such circumstances.

Moreover, it was pointed out that the arrangement depicted in Fig. 13 possessed certain advantages when operating in conjunction with currents of low power factor. In the same figure a displacement transformation possessing no restraining element was shown, but it was mentioned that it might be expected to be present in practical applications of the device. This is illustrated by the present example in which overload restraint is applied to this second transformation, the resulting diagram being shown in Fig. 44. Under conditions involving heavy "through" currents correspondingly greater secondary currents will flow in the circulating-current circuit in which the overload restraining windings are connected, and the apparatus will thus be rendered less sensitive to any unbalancing effects that may be set up.

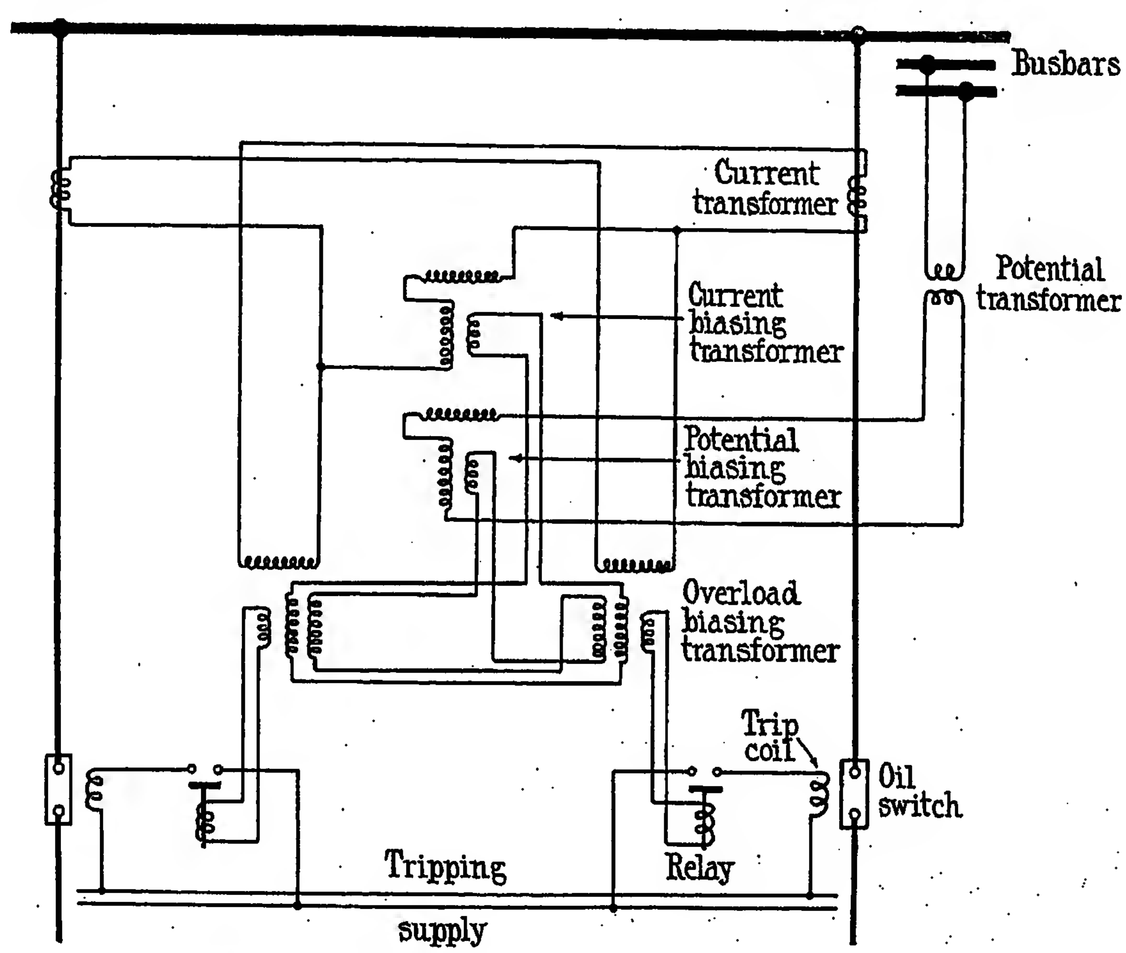

Fig. 44.—Balanced-power circuit compounded by current.

The diagram differs in arrangement from Fig. 43 in certain other features, including a certain simplification in the connections. For instance, instead of the two operating windings excited differentially by the current transformers one only is necessary. Moreover, it is found possible to dispense with one of the potential biasing transformers, the necessary excitation from this source being provided by a single unit. Although, for reasons of detail, the connections in this respect are not entirely in accordance with those indicated in Fig. 13, their effect and function are identical. It is in general desirable to reduce to a minimum the energy output from potential transformers, and by the use of one biasing transformer unit only, excited from this source, the volt-ampere consumption is exactly halved.

A further characteristic of utility, however, may be provided by the circuit indicated in Fig. 44. This may, perhaps, be more easily explained if attention is once more directed to the operating conditions peculiar to directional systems. It has been pointed out that the special circumstance rendering essential the provision of such gear, rather than apparatus operative by current alone, is the protection of two incoming feeders. It will be seen that the portion of the fault current which affects the protective apparatus concerned will be present in both sound and defective feeders. Load currents, therefore, being for the moment neglected, the current transformers will be excited by currents equal in magnitude, though the power represented by these currents will be opposite in direction. It is thus evident why current-balancing apparatus will be inapplicable in this instance, and if the effects of load current are now considered it will be realized that it is possible under certain conditions for the sound feeder to be carrying the heavier current.

If this particular circumstance be examined in regard to Fig. 44, it will be noticed that under the conditions specified, i.e. when a fault is being fed from the generating station through the substation busbars, neglecting load current there will be present in the two overload restraining windings equivalent currents equal to exactly one-half of that flowing in the operating winding due to the fault. In order to obtain correct directional operation it is evident that the relation between the current in the differential operating winding and that in both of the relays should be precisely in accordance with Fig. 12 (*a*), potential excitation being for the moment disregarded. The apparatus, therefore, is designed so that this result is achieved with the specified flow of current.

Whilst it has been pointed out that this arrangement is particularly associated with double feeders at their receiving ends, such apparatus may be installed at both ends where the normal flow of power may be in either direction. Under other conditions the occurrence of faults may sometimes set up such a flow of current that balanced-current gear would correctly discriminate. That is to say, there will be in the defective feeder a current greater than that in any adjacent circuits.

Another condition relevant to the point under discussion is the existence in a receiving substation protected in this manner, of live loads, e.g. rotary converters, motor-generators, etc. It has been stated that where a fault is fed through a substation containing no source of generating plant as such, the currents in the sound and faulty feeders may be equivalent in magnitude. It often happens, however, that when a sudden short-circuit occurs transient balanced-current conditions may exist due to the momentum of rotating machinery; in other words, it is possible that the substation plant may feed into a fault immediately it occurs.

It is generally felt that of all the various methods of protection available, potential-operated arrangements are the least reliable. It is thought, therefore, that desirable features may be provided in apparatus of this nature if advantage be taken of the occurrence of such circumstances as have just been referred to.

In the circuit shown in Fig. 44 it is found possible to arrange that the apparatus functions correctly in a purely directional manner in conjunction with potential excitation when this is necessary, and that when balanced-current conditions obtain, i.e. when the faulty feeder is, in fact, carrying a greater current than any other, the operation of the protective gear may thereby be assisted and rendered more certain. The apparatus is accordingly designed so that the relay current, as in Fig. 12 (*a*), is produced by a flow of current corresponding to the direct effect of a fault flowing into and out of the substation bars, such current-flow exciting the gear in question.

In Fig. 45 curves resembling Fig. 12 (*a*) are again shown. Curve (*b*) in Fig. 45 is, in fact, identical with that shown in Fig. 12 (*a*).

If consideration be now given to the flow of current in the operating and restraining windings occurring when the conditions are such that the current in one

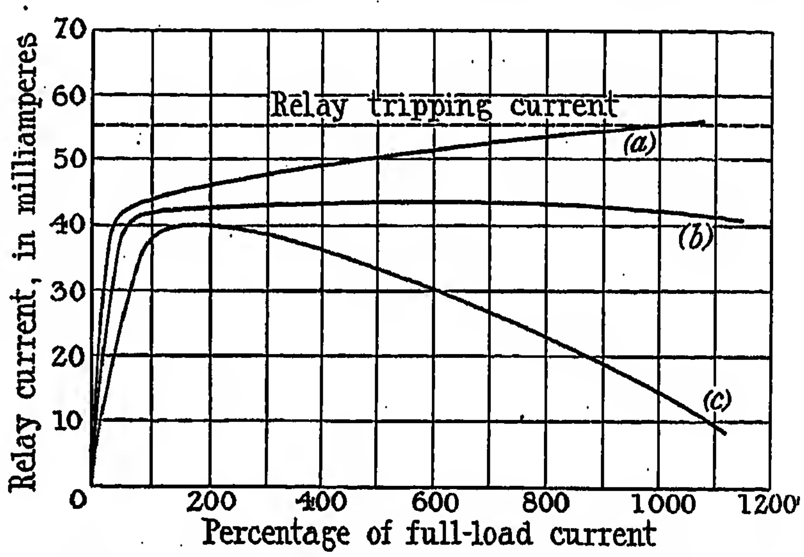

FIG. 45.—Characteristic curves of biasing transformer compound directional operation.

feeder is very much greater than that in another, it will be seen that, in regard to the relay associated with the feeder carrying the heaviest current, there would be a restraining current less than one-half the operating current. On the sound feeder, however, the restraining current would exceed one-half the operating current. Curve (*a*) in Fig. 45 indicates the excitation produced by the former circumstances, and curve (*c*) refers to the latter. As in Fig. 12, the effect of potential is not referred to.

The effect of this arrangement on the operation of the relays is as follows:—

It has been explained in Section 1 and in regard to Fig. 10 or 14 that relay excitation, according to curve (*a*) in Fig. 12 [that is, curve (*b*) in Fig. 45] causes tripping of the relay over approximately 180° of phase relation, the relay being inoperative throughout the remainder. It will therefore be seen that if the relay current be increased, as shown in Fig. 45 [curve (*a*)], the relay will be operative over a greater angular range. In fact, it is found that in the event of complete extinction of voltage, tripping of the relay will still

occur on a very severe fault, due to the curve intersecting the line corresponding to the relay tripping current.

On the other hand, in the case of a healthy feeder the excitation of the relay due to current is so reduced, according to Fig. 45 (*c*), that the relay is operative over a smaller angular extent than 180°. Moreover, if the fault is sufficiently severe it will be impossible for the sound relay to trip, no matter what the phase relation between current and potential may be.

Thus in the case of a rotary substation fed by a double feeder, the effect of a sudden surge of power due to the mass of the rotary armatures feeding a fault on one of the feeders would increase the tendency of the faulty relay to trip and would help to keep the healthy feeder immune.

In Fig. 46 the complete wiring diagram appropriate to the protection of a double feeder on the above lines is shown. This arrangement is equally applicable to the protection of a double interconnector. It will, however, be necessary to provide auxiliary switches, and it will further be essential that the fault settings employed shall exceed normal load currents for precisely such reasons as have been fully explained in regard to the protection of generating ends of feeders.

Improved form of balanced-power circuit.—The evident advantages which accrue in the case of balanced-current protection by the use of apparatus capable of differentiating between line faults and earth faults render very desirable the achievement of similar methods in regard to directionally operated protective gear. Not only does the employment of this principle preclude interference with normal switching operations, but in general it enables increased sensitivity in regard to earth faults to be achieved, due to the fact that reduced disturbances in connections, peculiar to leakage faults, are set up in the protective circuit when the feeders concerned are subjected to heavy overloads or line faults. It has hitherto not been found possible to achieve this result on a commercial scale.

Means of providing for a flow of current in the secondary circuits of a protective system directly due to leakage faults are well known, but, in order to discriminate in accordance with the direction of the leakage fault, this must necessarily be referred to the potential associated with the phase on which the fault occurs. Previous methods have arranged for this by connecting the potential elements of the relays between an artificial or other neutral point in the supply system and earth.

Normally there will be no potential between these two points, but on the occurrence of an earth fault a potential difference of a value depending on which of the phases has suffered the fault will exist. Objections have, however, been raised to the additional potential connections involved, and this particular arrangement would not appear to have been largely employed. In the present instance a solution of the problem has been sought in a different direction. Instead of providing a special leakage relay, as in the balanced-current gear, a triple-pole relay is used, each pole being responsive to faults on the corresponding phase. Special means are provided whereby the relays become energized to a greater extent on the occurrence of an earth fault than will be the case where line faults are concerned.

The relay, therefore, whilst itself operating at a constant value of sensitivity, is more easily tripped by earth faults than by line faults. It is necessary, therefore, for a system of connections to be devised in which an augmented flow of current shall be set up on the occurrence of a leakage component in the energizing circuit. Instead, however, of this additional current appearing in a single neutral lead, it must be present

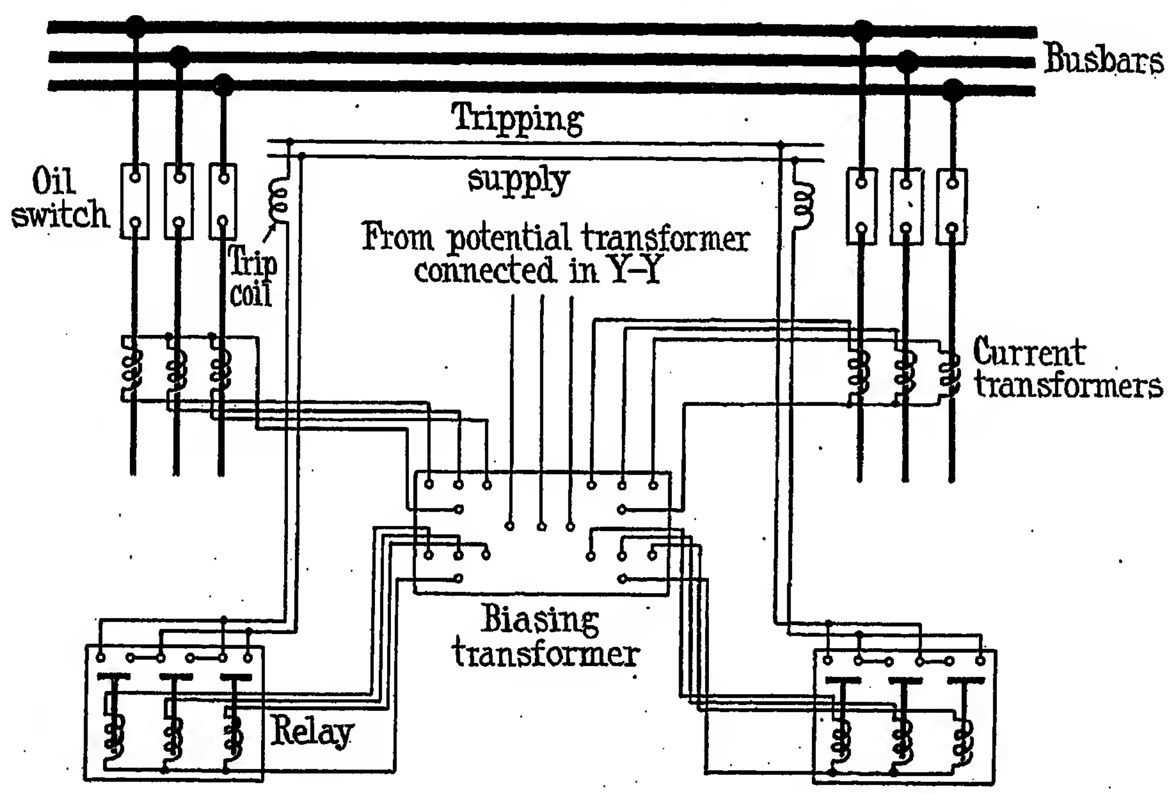

FIG. 46.—Wiring diagram of balanced-power system.

in one of three directionally operative circuits, according to which phase has suffered the earth fault. It is evident that only in relation to the potential associated with the faulty phase may proper directional discriminating operation be achieved.

An application of the principle employed is illustrated in Fig. 47, in which current connections only are shown. It is to be understood that this arrangement will in general form a "difference" circuit and that the secondaries of the biasing transformers will supply directionally operative relays, or the equivalent biasing transformer circuit already described. For the sake of clearness, only those connections relevant to the particular principle to be explained are indicated in the diagram. The three windings shown at the top of the figure may therefore be considered to be the secondaries of current transformers or any other similar source of three-phase current. They excite three biasing transformers, a common or neutral return being employed in the usual way. Each biasing transformer has two operating windings and two restraining windings and is provided with a single secondary for energizing the directional relay, etc., referred to above. It will be seen that one of the operating windings and one of the restraining windings are connected in series with each phase, whereas the other operating and restraining windings are connected in series with the neutral lead between the common point of the biasing transformers and that of the energizing transformers. The number of turns on the two restraining windings will be similar.

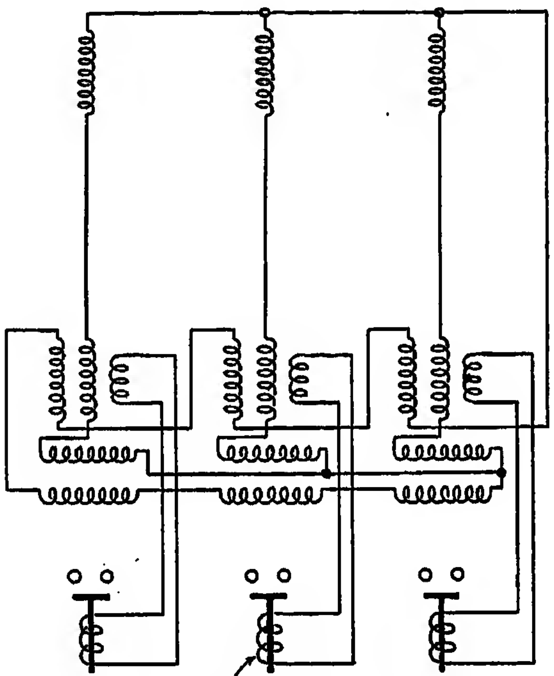

FIG. 47.—Diagram of biasing transformer arrangement for sensitive directional operation on earth faults.

If a current be considered to flow in the secondary of one current transformer only, returning via the neutral lead, then the two operating windings mentioned are so arranged that their exciting ampere-turns are additive. Further, under this condition it will be seen that the two restraining windings are in opposition, and there will therefore be no restraint at all on the biasing transformer appropriate to the phase which has become energized. The secondary of this transformer will receive maximum energy. If the current transformers, however, are excited by currents which have no leakage component, there will be no current in the neutral wire nor in the corresponding operating and restraining windings.

The turns on the biasing transformers are so arranged that the energy in the secondary, due to either restraining winding and operating winding in series, is such that the current in the relay is negligibly small and cannot possibly affect operation.

It will be seen that when a leakage current occurs it traverses the operating and restraining windings on all three of the biasing transformers. On two of them the restraint will be effective, and negligible energy will be applied to the secondary windings. On the one associated with the phase in which the leakage current flows, however, it has been seen that the restraining windings are in opposition, and accordingly there is no restraint. This arrangement therefore provides that an earth fault current on any phase operates the relay only in conjunction with the potential appropriate to that phase.

The simple arrangement shown in Fig. 47 does not function entirely correctly on the occurrence of simultaneous earth and line currents in opposite directions, but it is applicable to a number of conditions, more especially in connection with differential circuits, and in other cases special means may be taken to overcome the difficulties referred to. If therefore the apparatus shown in Fig. 47 be now considered to be excited differentially, after the manner indicated in Figs. 43 and 44, it will be seen that it will only become energized on the occurrence of a fault between lines or to earth on one or other of the feeders protected. In the complete protective circuit, therefore, will be found all the features enumerated in regard to Fig. 44, plus the additional characteristics peculiar to Fig. 47. It is not, however, considered essential, in connection with earth faults, to take into account severe disturbances in the voltage of the system, nor in general will faults occurring on systems operating with an earthing resistance give rise to highly reactive currents flowing to earth. Accordingly the phenomena associated with Figs. 14 and 45 are not arranged to be present in the operation of leakage faults, since both these conditions refer especially to circumstances accompanying the existence of fault currents approximating in value to the short-circuit current.

The leakage discriminating biasing transformers are therefore added to the arrangement shown in Figs. 43 and 44, their secondaries being connected in series with the existing secondary circuits which energize the relays. The operation on line faults is unaffected by the addition and is as described in connection with the above diagrams. The provision of the extra biasing transformer units will slightly modify the dimensions of the biasing transformer shown in Fig. 46, and there will necessarily be a number of additional connections inside the biasing transformer. It is not found, however, that the addition of the circuits concerned with

leakage sensitivity in any way adds to the connections external to the biasing transformer. Fig. 46 shows the complete arrangement appropriate to the protection of a double feeder at a receiving end by means of apparatus of the general nature described.

An entirely analogous arrangement appropriate for the protection of multiple feeders might be provided, it being understood that the apparatus is chosen with a view to operation from time to time with only two lines in service.

The following performance may be provided with this gear, utilizing exactly the same relay as has been referred to in connection with all other schemes mentioned in the paper, namely, an attracted-armature relay capable of operating at about 0·5 volt-ampere.

It is found possible to provide settings which give rise to tripping of the relays on line faults on the occurrence of difference currents of the order of twice full-load current. Due to the effect of the power factor of the fault, definite figures of sensitivity cannot be specified without the provision of special curves of performance. In general, however, it is found that, due to the phase displacement action and other circumstances, the figure would lie between twice full load and four times full load, although different settings can be arranged if desired. These figures give complete freedom from disturbance under all normal conditions of operation. On the occurrence of an earth fault, however, the appropriate pole of the relay would trip on difference currents in many instances considerably less than 20 per cent of normal full load.

As indicated above, no extreme abnormality of potential is considered in regard to the clearance of leakage faults, but these conditions are particularly envisaged in connection with line faults. Single-phase faults, which cause distortion of the normal phase relation, are correctly cleared due to the connections employed. For the same reason, reduction of pressure between the faulty phases, due to impedance drop, will not affect the operation.

Where the fault gives rise to fall of pressure, due to reaction in generating plant, the sound phases, between which the potential connections in question are excited, may be affected, but to a less extent. In the event of a complete short-circuit occurring simultaneously on all three phases, the apparatus is found to function at pressures down to 25 per cent of normal pressure. It is realized that this figure compares unfavourably with the performance possible with dynamometer relays of suitable type, but it may be improved in proportion to the amount of potential excitation employed. It is felt that the more simple installation may present advantages which may be offset against the above shortcoming, which is particularly associated with the type of relay employed. Moreover, an accident of the nature referred to is distinctly uncommon and is hardly possible except as the result of a switching error, such as is commonly guarded against by interlocking. Experiments made by the author on testing circuits in connection with this type of gear, in which short-circuits were applied by dropping a bar across the three phases, almost invariably resulted in the fault clearing as a short-circuit between two phases.

It must be pointed out that the above figures refer particularly to actual balanced-power conditions, i.e. to a receiving substation supplied by two lines. Whenever differences in current magnitude occur, these figures will be improved upon, tripping being possible in severe circumstances with no potential at all on any of the phases.

Use of dynamometer relays.—In the arrangement described, the employment of a simple relay operating directionally after the manner described in Section 1 was indicated. It may be of interest to point out, however, that the special characteristics, such as overload restraint and sensitive leakage, that may be provided by a biasing transformer of the form just described are not inseparable from such an arrangement. A dynamometer type of relay which, as indicated, is essentially an instrument of greater precision than the contactor type of relay, might be employed with very little departure from the connection shown in Figs. 44 and 46.

Section 3.

Application.

The selection of means of protection for any given system or item of plant will call for consideration of the following circumstances:—

(i) The capital value of the plant protected.

(ii) The value of the service, either directly or indirectly. By this is meant the cost per minute to the supply company of an enforced shut-down or, alternatively, the extent of the inconvenience experienced by the consumers and corresponding loss of goodwill, etc.

(iii) The arrangement of the machines, transformers, feeders, etc., necessitated by the conditions of supply.

(iv) Whether the circuits to be protected already exist or if they may be laid out with a view to the provision of efficient protective gear.

Generating and distribution systems, for which it may be necessary to specify means of protection, may be broadly classified as follows:—

(*a*) Those in which the importance of continuity of supply and the expenditure already incurred by the provision of large and costly generating and control units fully justify the additional cost of installing what is considered to be the most suitable and reliable method of affording adequate protection.

(*b*) Systems in which the nature of the load supplied and the value of the plant installed do not warrant more than a limited investment in protective gear, or where, on a lay-out already existing, the provision of such apparatus is only possible to the extent of the installation of additional switches, relays, etc., as distinct from the laying of special conductors or the rearrangement of existing connections. The measure of discrimination obtained in such cases depends to a large extent, in the case of feeders, on the form of network involved.

(c) Small undertakings of limited plant capacity not in general subject to heavy disturbances due to faults, nor supplying loads of the nature in which an occasional interruption of supply gives rise to more than momentary inconvenience. Parallel feeders will not frequently be found on such systems, and instantaneous discrimination is usually limited to the simplest circuits.

So far as generators are concerned, the usual practice is to employ circulating-current protection with suitable field-suppression gear on all machines above, say, 1 000 kW at 3 300 volts. Biasing transformers may be usefully employed for the protection of generators on systems coming in the first category, where low fault-settings are specially desirable.

It is usual to employ circulating-current protective gear for all large transformers, and also for small transformers on important systems, where both primaries and secondaries are connected in parallel. Biasing transformers are particularly useful where low fault-settings are desired, or where the protective transformers have inherently different magnetizing characteristics.

Feeder protection has to be considered with reference to the classification of systems detailed above.

Systems (*a*).—Opposed-voltage protective systems have been more widely employed than any other form, since the use of a pilot wire enables any circuit to be protected without reference to the remainder of the system. It is considered that the particular form described in this paper possesses the following advantages over certain other combinations:—

(1) No sheath is required for the pilot wires.
(2) No air-gap is needed in protective transformers.
(3) Protective transformers are interchangeable.
(4) A low earth-fault setting is obtained with a robust relay.
(5) Immunity from incorrect tripping is obtained at very high currents.

Split-conductor protection, while avoiding the use of pilot cables, necessitates a special form of cable and usually more expensive switchgear, and there seems little tendency to install it at the present time, except for extensions to a system where it has already been used.

Systems (*b*).—In systems of this character, the operation of feeders in parallel permits the use of discriminating protective gear without serious expenditure.

In general, balanced-current gear is chosen for the transmitting end and balanced-power gear for the receiving end. A low earth fault-setting and a relatively high line fault-setting is provided, so that feeders may be switched in and out of circuit without consideration of the protective gear. This protective gear will operate even if the line potential has fallen to zero, except in the case of two incoming feeders at a substation, and even there the potential connections are so arranged that correct tripping will occur with any two lines short-circuited. In practice it has also been demonstrated with an apparently instantaneous three-phase short-circuit.

Systems (*c*).—There is little chance of discrimination in systems of this character, and it is usual to install leakage trips and graded overload time-limits. In certain cases a reverse relay with sensitive leakage setting can be used with advantage.

Conclusion.

Advantages in use of biasing transformer.

(1) Any type of relay may be used.
(2) A single type of simple relay may be used for any of the systems of protection described.
(3) Different forms of biasing transformer may be made of standard components.
(4) Transformer-operated relays are not disturbed by stray direct currents.
(5) The relay is protected from mechanical damage due to heavy faults.
(6) The apparatus requires minimum attention.
(7) Static discriminating apparatus is not likely to deteriorate under service conditions.

Advantages of separate line and earth settings.

(1) Sensitive operation on earth faults is more easily achieved.
(2) Sensitively set relays are not disturbed by short-circuit currents.
(3) Ring cores may be used for opposed-voltage protective system.
(4) Parallel-feeder protective system not disturbed by switching.
(5) Small "tee" loads on protected feeders are possible without interfering with protective arrangements.

Finally it may be mentioned that the British Thomson-Houston Co. have subjected all the devices described in the paper to such tests under service conditions and also at the factory as are essential to prove their practical capabilities, and that exhaustive experiments have been carried out on each of the complete protective circuits, special arrangements having been made to simulate the various service conditions which it has been possible to foresee and reproduce.

Of the eight principal systems of protection described, actual equipments have been supplied except in the cases of two systems, in lieu of which other methods described in the paper are available.

In conclusion, the author desires to thank the British Thomson-Houston Co. for their kind permission to publish the results of investigations largely carried out at their works, and also particularly to acknowledge his indebtedness to Mr. H. Trencham for setting forth the conditions to be met and for his guidance during the progress of the work involved.

DISCUSSION BEFORE THE INSTITUTION, 28 FEBRUARY, 1924.

Captain J. M. Donaldson: The author suggests that a balance be struck between the cost of the apparatus and that of a shut-down, i.e. the loss involved by a catastrophe which the apparatus is designed to prevent. That is a very sound proposition, but one not very easy to carry out. One point which is sometimes overlooked by the makers of protective gear is that such gear may introduce another weak link in the chain. The majority of feeder protective systems depend upon the use of a pilot cable, and sometimes this is of an expensive type. Indeed, in the case of certain installations it is obviously too expensive to be a commercial proposition. In the majority of cases a fault on the pilot cable will cause the relay to operate when it should not do so, or else the protective gear may be absolutely out of action without the fact being known. I suggested to one maker that it might be a sound scheme to have in the pilot circuit a small direct current, the primary object of which would be to show by its presence on an ammeter that all was well, and the result of such an arrangement might be to increase the sensitiveness of the relay. I was informed, however, that this would be impracticable because the relay setting would be altogether too delicate and would not work. I merely wish to point out that in this particular case the addition of a necessary component of protective gear seriously increases the risk, because troubles on feeders are generally due to mechanical reasons. A large three-phase generator will, according to modern fashion, have a full array of protective transformers. It will certainly have six—three on each side of the main winding—to cut the machine out if internal trouble develops. Then there will be three more transformers the duty of which it is to provide for metering and for recording purposes, and possibly another for the pressure regulator. I believe that the current transformer does form a weak part of the system; moreover, it needs housing accommodation. All these things make for complexity, and each point of complexity is an added source of trouble. For that reason, the author's biasing transformer seems at first sight to add another link to the chain. I think, however, that this is more apparent than real. The biasing transformer, with an ordinary relay of a more rugged type, takes the place of a balanced type relay, and the author's argument would be that his biasing transformer, plus the simple relay, is certainly no more complicated and can be made more reliable than the old arrangement. I think that if the author's claims in regard to the apparatus are justified—as I have no doubt they are—there is a great deal to be said for it. Those who have had experience of protective gear know that often it will operate when it should not do so, or vice versa. The capacity current is often blamed, but, I think, not always correctly. I have found on feeders split up into various sections and controlled by Merz-Price arrangements, that whereas a certain group of transformers will act correctly, or fail to act correctly, another group on precisely the same feeder will do exactly the opposite. The broad principles of design are the same, yet there is this difference between the different makes of transformers, and the answer is obviously that the source of the trouble is not the capacity current but the lack of balance between these current transformers. If, then, the biasing transformer will eliminate such troubles, it is certainly worth a minor degree of complication, and, of course, if it also enables us to do away with the Merz-Beard sheath, that is an advantage which I, for one, shall welcome with enthusiasm, because that sheath is an expensive item when a cable which in itself is not very expensive is being protected. I feel that we are rather apt to legislate at considerable expense for conditions which seldom arise. Of course, one must make up one's mind as to whether an occasional breakdown is to be risked. This may sometimes happen, even if protective gear is installed. There is a good deal to be said for taking a certain amount of risk, as against the method of having everything absolutely invulnerable. A very considerable degree of simplicity can be obtained by omitting relays altogether, not in the sense of refusing to have protective gear of any sort or kind, but by letting the current do its own work unaided. There is at present on the market a device which, by the movement of the operating handle, stores up a certain amount of energy which can be released at the proper time by pulling down a small armature, and I think that this does get over the difficulty a good deal. The relays used in this arrangement are of the size of telephone relays. Among the other troubles attaching to protective gear is the fact that a short-circuit is accompanied by a great deal of noise and a certain amount of vibration. I have known several cases in which relays have operated when they should not have done so, merely on account of the vibration caused by the short-circuit. It has also to be remembered, of course, that the use of a relay almost invariably necessitates some kind of switch of an auxiliary character. I agree with the author that less attention has been paid in the past to these auxiliary switches than they deserve.

Lieut.-Colonel K. Edgcumbe: The author points out that one of the great difficulties met with by the designer of protective gear is the enormous range of currents with which he has to deal. The figures given by the author have a range of 1 to 400. This presents a very real difficulty, because nearly all protective systems depend on a balance between two currents which, under full-load conditions, are very large. The author's scheme is to render the relays less sensitive as the overload increases, and he has certainly done this very effectively. But there are two other methods whereby the difficulty can be overcome. One is to improve the current transformers. The author starts out with the assumption that the current transformers are bound to give bad balance. I do not think that that necessarily follows. The current transformers of which I speak are not the balanced-voltage type mentioned by Captain Donaldson, but ordinary current transformers. The question of balance resolves itself into one of having sufficient primary ampere-turns and making the trans-

former do as little work as possible. The transformer now in general favour is the single-turn type in which one conductor passes through a core. A current of 100 amperes flowing in the feeder at full load gives only 100 ampere-turns, and this is very small for the purpose of a transformer. The popularity of this transformer is due partly to its cost—the transformers are cheap to build—but partly also to the reduction of insulation troubles and the mechanical strength to resist short-circuit. In physical measurements it is bad practice to measure a small quantity by a method which involves measuring two large quantities and taking their difference. What one tries to do is to get some method of measurement whereby what one measures is the actual difference itself. Similarly with protective schemes, in which case it so happens that it can be very simply done with current transformers operating on the core-balance principle. If the three phases of a three-phase feeder are passed through a current transformer, the secondary current of that transformer will correspond to the difference extremely accurately. Therefore, any question of the dissimilarity of the transformers is eliminated. The author points out the great importance of keeping the leakage discrimination and the overload discrimination quite distinct, but I do not think that he pushes that idea to its logical conclusion. If they are kept quite distinct it means that the range which one has to cover, instead of being 400 to 1, becomes something like 5 to 1 in the case of leakage, and perhaps 10 to 1 in the case of overload. Those are ranges which the ordinary current transformer, if properly constructed, can easily cover, and bias thus becomes an unnecessary complication.

Mr. J. R. Cowie: I am in agreement with the author when he advocates the use as far as possible of a straight-bar primary in current transformers. An endeavour has often been made in the past to obtain a sensitive tripping device by means of multiple-wound current transformers and/or cutting down the amount of iron in the circuit, generally leading eventually to trouble due to surging current, etc., making the device operative when it should not function. The author's scheme appears to some extent to be on similar lines. At the first glance it would appear that the sensitive settings claimed by the author cannot be obtained because he is using a restraining device on his relay, but on going further into the matter one finds that he is advocating the use of practically solid-core transformers having a higher driving force than multi-gap transformers, and he is balancing one fact against the other. Personally, I think that he is not correct in so doing and that the proper place to get the requisite balance and characteristic is in the transformer itself. This can quite easily be done and a balanced characteristic for fault currents can be obtained much in excess of any figures shown in the paper, a robust, simple and sensitive relay still being retained. It seems to me that the main application of the author's device will be on a line which is giving trouble because a system has outgrown the older types of protection originally installed. The author again raises the question of parallel-feeder protection and employs his biased transformers for these devices, but parallel-feeder protection is known to be fundamentally wrong in that the operation of the relays, no matter what their type, is at the mercy of the load current, and such apparatus may function, may not function, or may function incorrectly. If parallel-feeder protection were a satisfactory device, the Merz-Price system would not have come into existence, nor would split-conductor protection or other discriminating forms have been evolved. On page 585 the author advocates the use of his device on split-conductor apparatus. Such an addition appears to me to be unnecessary, and this is best illustrated by a few practical examples. At one time I had to control a system where two 0·2 sq. in. 3-core cables were joined in parallel on one split-conductor switch and an important converting station of some 5 000–6 000 kW capacity was fed from the end of the line. An industrial load of 250 kW was tapped off one of the 3-core legs and this worked in an entirely satisfactory manner for a number of years, but was afterwards balanced out with an additional leg from the second 3-core cable when this practice was commercially justified. My point is that it was found possible to work without using any auxiliary device where a failure would have meant disaster. In another instance, two 3-core cables in parallel were satisfactorily used where the difference in length of two legs was some 7 per cent. I should like to emphasize the fact that fault settings with this simple device are in the region of 25 to 45 amperes, either between phases or to earth, independent of the length of the line. This condition cannot obtain with the author's device. Split-conductor protection is the most sensitive and stable form of protection of which I have knowledge, and I have yet to see it operate incorrectly on straight-through fault currents. There is a third example working in this country of an overhead 20 000-volt split-conductor line in which the step-up and step-down transformers are included within the zone of split-conductor protection. At present the line is carrying some 10 000 kW and at a future date will carry 20 000 kW. On the secondary side of the transformers there is a relay which will indicate which side of the line has developed a fault, and devices which will permit the engineers to switch in again on the sound half of the line until such time as the fault can be repaired. It should be noted that no charging devices are fitted in the switch. The author claims that his device will take care of the case where a faulty joint has been made in a split-conductor cable. I have had experience of such a joint, and the standard split-conductor protection showed it up. One wants a device which will show up an incipient fault on the system and not hide it. Sensitive settings appear at the present time to be in favour, but in my opinion these indicate a very retrograde step. The fault currents which any system can give are inherent to the system, and nothing that can be done in the way of protective devices will reduce the magnitude of this fault current. If, as I think the author suggests, a smaller earthing resistance should be used, there is a great danger of leaving a large percentage of his alternator windings unprotected. This matter was fully dealt with in Mr. Kuyser's paper,* and need not be stressed further.

Mr. R. W. Biles: The paper may be summed up as

* *Journal I.E.E.*, 1922, vol. 60, 761.

an application of a biasing transformer to all the well-known balanced systems of protection. The question naturally arises as to why the use of a biasing transformer or any stabilizing device has been found necessary. The answer is that a demand has arisen for very sensitive operation. To obtain this sensitive operation many engineers fit some device to limit the flow of current in the case of a fault to earth, and this usually consists of a high resistance in the neutral. The question is a very difficult one to decide, since experience varies to such a large degree, and it depends chiefly upon the local conditions. I would suggest that engineers should take more pains to measure the ohmic value of the earth from the remotest point of the system. The method of bonding the earthing leads is important, as is also the number of points that are earthed on the system. Multiple earthing requires very careful consideration and many protective advantages can be gained by its use. Personally, I favour earthing through no resistance at all, and it is quite obvious that in the design of any protective system allowance must be made for a heavy flow of current in the case of faults between phases, and no high ohmic value of neutral resistance will tend to diminish such a large flow of current in view of the possibility of simultaneous earth faults. The effect of earthing solid is also to ensure clearance of all earth faults, which is a very valuable feature. In some cases also it is useful to have a low operating setting consistent with stability, with the result that only a negligible risk is run of a fault occurring on the system of a value insufficient to operate the protective gear. I have no doubt that the author applies a bias transformer chiefly for this purpose and not for use with a high neutral resistance. He very ingeniously applies it for use with crude current transformers, which require no balancing during manufacture, but it is questionable whether any

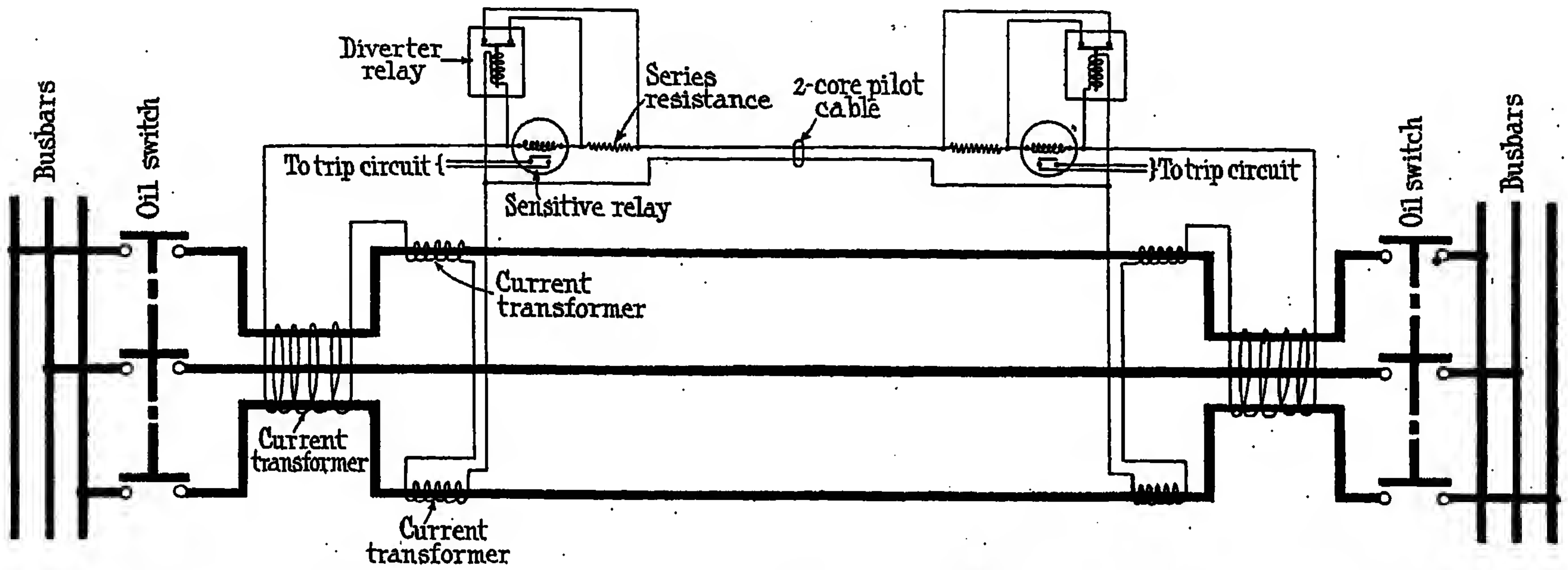

FIG. A.—Diverter relay applied to combined balanced earth leakage and Merz-Price protection; for low fault settings.

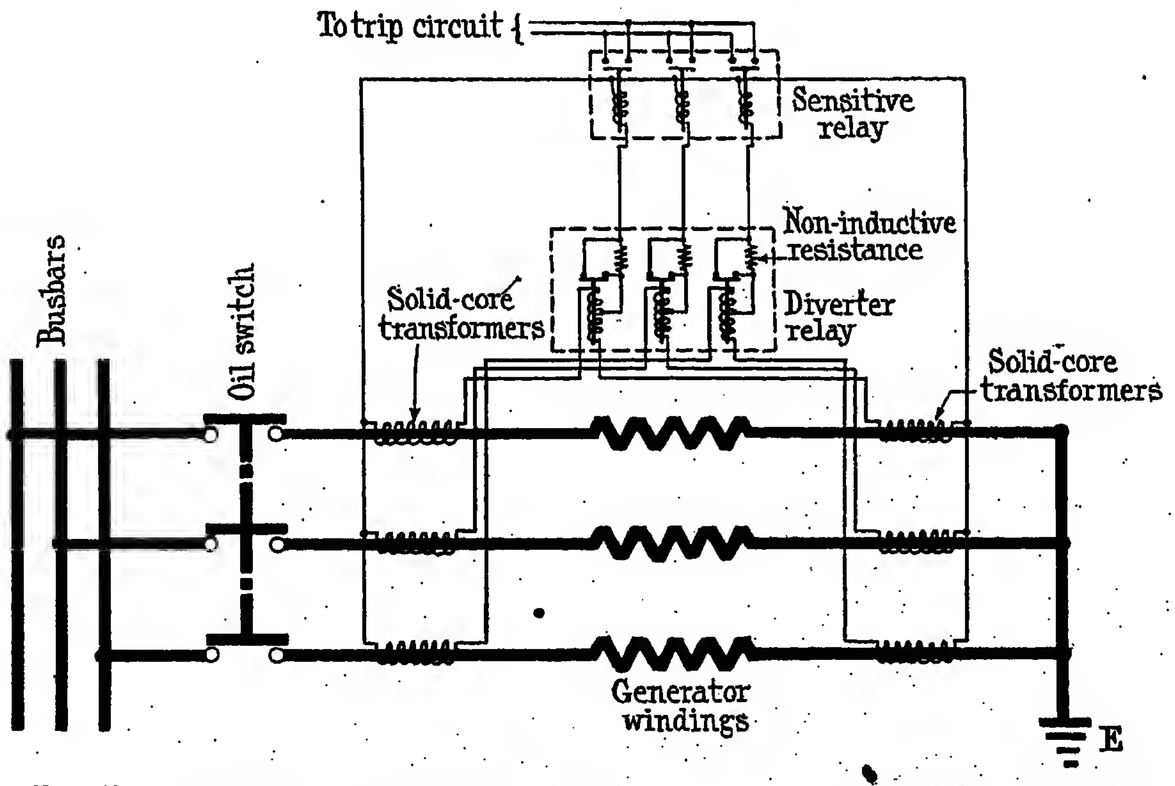

FIG. B.—Diverter relay applied to generator protection; for low fault settings.

economy is effected by this. In any case the cost of the extra bias transformer must be offset against the simple balancing tests that are required. The bias transformer is specially constructed and wired, and requires skilled attention during testing. The difference between a balance transformer and a crude transformer is the simple adjustment of the iron circuit before the windings are put on. I mention this because one of the author's criticisms is the difficulty of balancing. My experience is the contrary, and very little saving is effected. Captain Donaldson, in opening the discussion, made a plea for simplicity; whilst it is a great ideal it is often difficult to achieve, especially in circumstances where sensitive settings may be required. Fig. A shows an alternative arrangement employing a diverter relay. The diagram illustrates the arrangement of three current transformers at each end of the line. The secondary windings are connected in series with two single-pole relays, one at each end of the line, and a two-core pilot cable. Across the pilot cable, also at each end of the line, is connected the diverter relay. The operation of the relay increases the setting of the sensitive relay by introducing a resistance in series. The sensitive relay operates at something less than 0·1 sec. and the diverter relay works at a high speed approximating to 0·01 sec. The arrangement is particularly economical and has the following advantages: (1) Two-core pilot cable only; (2) two single-pole operating relays; (3) sensitive earth-fault protection; (4) stability against overloads; (5) stability against pilot capacity current; (6) no sheaths are required for the pilots; (7) air-gap is optional in current transformers; (8) protective transformers are interchangeable; (9) robust relays may be employed; and (10) same sensitive setting for faults between phases as for earth faults. The advantages over the author's proposals are Nos. (1) and (10). The diverter relay is equally applicable to generator protection and, in fact, any system of balanced protection. In the case of the protection of generators (see Fig. B) the diverter relay is connected in series with the pilot wires, where a current-balance system is used. Settings as low as 4 per cent of full load have been demonstrated with perfect stability and with unbalanced current transformers. The use of this setting may be permissible in certain circumstances. For feeders on a 10-mile line, earth-fault operation can be obtained between 50 and 70 amperes. If wound primaries were used on the same core this value would be considerably reduced. In conclusion, I would say that although I appreciate the author's effort towards the solution of parallel-feeder protection, I am not convinced that the proposal is satisfactory under a simultaneous three-phase fault condition. Such a condition is very unlikely, but when it does occur it is very serious.

Mr. H. Trencham: I should like first to refer to the matter of distinguishing between faults to earth and faults between phases. It is customary to hear engineers deploring the large amount of money which has to be spent in switchgear and switchgear apparatus generally. Phase faults are largely the cause of this outlay and, if the general practice of the industry be examined closely, it will be found that a very determined effort is being made to eliminate such faults. Engineers in the United States have gone so far as to build what substantially amount to separate switch-houses for each phase of a three-phase circuit, and it seems to me that if phase faults can be definitely avoided or if they can be reduced to that small proportion which Captain Donaldson suggests may be regarded as negligible, one is thoroughly justified in legislating for every benefit that earth leakage protection can give. It seems to me that the justification of working with earth faults instead of phase faults will be amply demonstrated if in the future we can use switchgear which is proportioned to deal only with currents such as occur under normal load, because abnormal currents are impossible. It stands to the credit of this country that switchgear which bids fair to meet this condition has been built, and built to a size and at a cost which, I submit, will compare very favourably with that of a scheme such as involves three separate switch-houses for a three-phase equipment. I am referring to totally enclosed or ironclad gear. In the larger sizes of this class of equipment it will generally be found that a phase-to-phase fault is quite impossible. In the smaller size the insulation problem is sufficiently well in hand to make phase-to-phase faults almost an impossibility, although actually in many cases there is no definite earth partition between the phases. The logical following up and improvement of designs of this kind will, I think, in the not distant future provide us with a means of avoiding the very destructive faults and consequent troubles due to phase short-circuits. Captain Donaldson referred to protective gear in a way which is thoroughly typical of the user, as he stated that it does not do what it ought to do and that it does what it ought not to do. Yet the need for it is proved by the fact that it still continues to excite much interest. In addition, I think that the user is not entirely without blame in reference to the bad name which protective gear gets. I say this while quite recognizing the difficulty that has to be met in designing protective gear. It is designed for unknown conditions or, at least, for the extraordinary or the unexpected condition, and makers have to imagine as well as they can what will happen, and provide for something to look after it. If protective gear holds a place in the economic world, then I think that it has not yet been treated with the attention it deserves. If one build a power station and install a steam turbine and a large generator, a great deal of money is spent in testing the equipment and making quite sure that it does what was specified, and, whilst recognizing the difficulties in the way of providing the unusual conditions which would be necessary thoroughly to demonstrate the efficiency of protective gear when installed, I think that they can be surmounted with the expenditure of very much less time and money than is habitually expended in looking after units larger and probably more spectacular. As contrasted with this possibility there are undoubtedly users in this country who have flatly refused to make any tests whatever on protective gear installed on site.

Mr. C. L. Lipman: How does the author propose to apply this scheme when the transmission pressures are

considerably increased? It seems to me that under such conditions it would be an absolute failure, as the extremely low ampere-turns of the line current transformer would be unable to provide the necessary power for energizing the biasing transformer, etc. This scheme is obviously meant to apply to future needs and conditions, so that it is necessary to forecast its availability in circumstances which are likely to arise in the future. I think that the scheme described in Fig. 9 is quite satisfactory, but it appears to me that it will probably cut out the sound feeder as well as the faulty one, and to prevent this the auxiliary apparatus is suggested. I think that this is a mistake, particularly when one realizes that it is possible to design a discriminating relay for parallel-feeder protection which will not cut out the sound feeder unless the load in the latter has increased by more than, say, 200 per cent above its normal capacity, after the faulty feeder has been tripped out. One advantage of the existing relays is that a person using them knows exactly what he is protecting against, and he can set the relay as he wishes. Another advantage of the existing directional (reverse-current) relay and discriminating relays is that the apparatus can be seen working and is often fitted with flag indicators giving positive indications of having operated in a certain way, but the relay as described by the author is an ordinary current relay and will never show in which direction it has operated. I should certainly advocate the practice of having a particular relay for a particular job.

[The author's reply to this discussion will be found on page 619.]

North-Eastern Centre, at Newcastle, 25 February, 1924.

Mr. H. W. Clothier: During the days of the development of Merz-Price balanced protective gear in this district, which commenced about 20 years ago, the following fundamental principles were definitely established: (1) The operation should apply to all conditions of fault, including earth faults, and short-circuits between phases and between all three phases and earth. (2) The protection should have universal application whether used on a ring main, parallel feeders, interconnectors, tees, etc., and should be made so that extensions to the systems by addition to feeders shall not necessitate alteration to the original protective apparatus. (3) There should be a rigid elimination of avoidable parts and connections. (4) Absolute stability under "straight through" fault conditions. (5) The avoidance of the potential element in relays, and the elimination of the potential transformer as a component of protective gear equipment. The author includes the following main features as they appeal to me: (*a*) The treatment of the much-discussed bias method in the Merz-Price protection by means of a biasing transformer in place of the biasing relay explored by McColl. (*b*) The development of this biasing transformer into parallel-feeder or double-feeder protection. (*c*) The combination of the principles of the old "core" leakage protection into balanced protection for feeders. Applying to all three the original subject matter we get the method of using an auxiliary transformer for introduction of the biasing effect, this being an alternative to the better-known system of biasing by means of relays. There is a further way of dealing with the problem known as the "diverter relay" system and in course of development by the Reyrolle Company, as illustrated in Fig. C. In both the transformer and relay bias the bias is always tending to restrain the operating relay. On the other hand, in the case of the diverter relay the restraint does not appertain until the straight-through fault current has approached a dangerous limit. At this stage the diverter relay operates and introduces a non-inductive resistance into the pilot-wire circuit. The resistance is such that the operating relay is insensitive to the maximum effects which would tend to cause inadvertent operation on straight-through fault currents, but it should be noted that it still remains responsive to internal fault currents though in a coarser degree of setting. The diverter relay system, therefore, has characteristics somewhat similar to those of the bias systems. It has the advantage that it is very simple and that it may be used in addition to standard air-gap transformers where a more sensitive setting is required than that procurable with the ordinary robust relay. In regard to the second

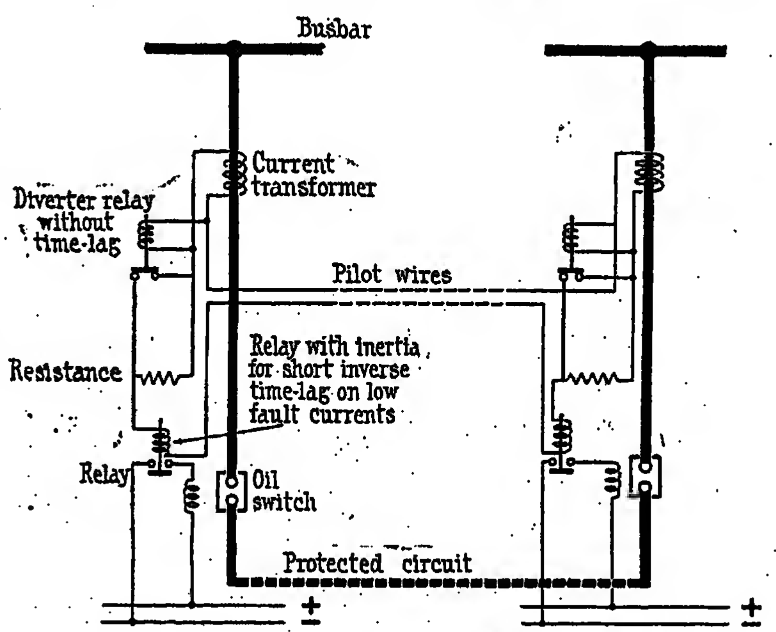

Fig. C.—Diverter relay applied to Merz-Price feeder protection for sensitive tripping.

feature, the development of the biasing transformer into parallel-feeder protection is extremely interesting and has entailed much thought. The ideal in parallel-feeder protection by interconnected balanced relays without pilot wire, after consideration of several stages of protective-gear development from time to time, has always appeared to me to be a myth. It is never possible to meet all the required conditions in service even when attempted in such an elaborate manner as is shown in the author's figures. I long since came to the conclusion that it was best to join the pair of feeders together and so form a simple split-conductor system which would allow both feeders to trip out for

a fault on one, and then the sound line, having overload protection, could be restored. In regard to the third feature, the use of core leakage in balancing with the pilot wire was considered on the North-East Coast network at one time, particularly in order to obtain the advantages of light settings for faults to earth which were thought to be advantageous for the protection of falling overhead lines. There was no difficulty in combining core-leakage protection with the ordinary air-gap transformer system, but the principle of balanced earth leakage was not generally accepted as a practicable solution for feeder protection. [It was only approved for generator protection (Porter system) and even in that case it did not reach a practical application stage.] The author mentions the reason on page 584. It is that, according to the experience on large power systems, a fault to earth on one phase is likely to be accompanied simultaneously by a fault to earth on another phase, and the second fault may be on another cable on another part of the system. The effect of this is to cut out the saving factor of the earthing resistance, and the fault currents to earth become practically as great as the fault current between phases. Therefore any considerations dealing with leakage protection must take into account straight-through currents of the same magnitude as those occurring on faults between phases. That being so, is there need to complicate the feeder-protected circuit by a separate system dealing with the earth leakage? The author does not state the fault-current settings for faults between phases, nor the measure of stability in terms of straight-through current which has been achieved by his bias system on feeders. It would be interesting to know whether any better results are obtainable with his solid-core transformers than with the air-gap transformer. The latter was found from the first stages of Merz-Price development to be the best means of obtaining stability under straight-through fault conditions. Later on it was improved by the introduction of a larger iron core and a multi-air-gap, proposed after investigations into the means of the avoidance of interference by external field which was experienced with the original single-air-gap transformer. At present most multi-air-gap transformers are adjusted and tested for balance with the standard up to 10 000 amperes. No difficulty is now experienced in manufacturing to comply with these tests, and accurate balance is possible under even greater currents. These precautions in manufacture have sufficed to meet the ordinary demand for feeder protection, using a simple relay having fault settings of 400 to 800 amperes when fed through one transformer at one end of the line only. It is remarkable that the simple treatment has survived notwithstanding the improvements suggested from time to time by many investigators who have studied the problems from the users' and manufacturers' points of view. Troubles there have been, but in the majority of cases these have been attributable to a mistaken endeavour unduly to cut down the operating currents, thus introducing a state of instability during straight-through fault currents. This has sometimes been done for no better reason than the saving in initial cost of the earthing resistance. It might be better in many cases to earth the neutral direct and save the whole cost of the earthing resistance, than to strive for ultra-sensitiveness at the expense of stability. Those instances where this special degree of sensitiveness is required may still be dealt with by the standard form of multi-air-gap transformer, utilizing the diverter relay method before mentioned. In this case the operating relay may be of the sensitive dynamometer type (such as the Fawssett-Parry) with inertia to avoid inadvertent operation on impulses, this being preferred to the author's solid-core transformers and biasing transformers. The leakage protection may be used in either case when it is considered to be safe. Two other phenomena which have been experienced on balanced protective systems have been more pronounced on systems of 33 000 and 66 000 volts in conjunction with very large power generation, and have not been disclosed by the author as a result of his practical investigations. One is interference by voltages induced on the pilot wire by heavy main single-phase fault currents. This condition may be aggravated by imperfect bonding of the main cable, allowing the return current to stray from the immediate surroundings of the cable. Inadvertent tripping of the relays occurs in the event of a pilot wire being earthed at one end, or when the insulation of the pilot wire breaks down. The remedy proposed by Mr. Porter is to add "drainage coils" to the pilot wire at each end, an expedient which is found necessary for a similar phenomenon in connection with telephone service. The other phenomenon is the production of an out-of-balance current in the pilot wire due to straight-through resonance currents occasioned by arcing faults to earth. In such cases there will be an actual difference of current in the two ends of the main line. It is, in fact, the exception to the principle upon which the Merz-Price balanced systems were originally based. Will the system of bias always take care of this? A convenient remedy is to make the relay inoperative by currents of frequencies other than the normal. This may be partially accomplished by shunting the relay coil with a non-inductive resistance, but a "reed" type relay is likely to be most useful for this purpose, the operating reed having the physical property of vibrating only within small variations from the normal frequency. These phenomena, however, are experienced only in the exceptional cases mentioned above. For the normal practical lay-out of cable systems for 6 000 to 20 000 volts, the original Merz-Price protection with multi-air-gap transformers and simple relays meets all service requirements, provided an unduly sensitive operation is not attempted. On reading foreign technical papers and studying practices in the application of protective gear in other countries, one cannot help but be impressed with the greater activities of British supply undertakings and manufacturers in the matter of efficient balanced systems of protection. Whilst other countries have tried to solve the problems with graded time-limit devices, the British industry has adopted the broader policy—notwithstanding the extra expense of the pilot wire or a special cable—of cultivating the art of true discrimination by the balancing methods. Unfortunately for the ideas in protective gear, it takes so long to explore fully a new method. Test-room

experiments do not always reveal the difficulties which occur under serious fault conditions on the network of cables with large amounts of power available. The bias system is no new thing, although the author's method in detail has not been on trial for long. No doubt, however, he will be able to assure us as to its efficient service on large power supply systems.

Mr. B. H. Leeson: The author, accepting the well-proved principles of balanced differential protective systems, has set out to obtain lower earth-fault settings, and, as a result, has devised a very ingenious piece of apparatus which he calls a "biasing transformer." The use of this additional apparatus is occasioned by the employment of solid-core unbalanced-type transformers, and this combination is advocated by the author as an alternative to the simple air-gap balanced-type transformer. This policy, however, does not harmonize with the principle of simplicity so rightly advocated at the beginning of the paper; and I question whether an extra biasing transformer is really necessary, seeing that an alternative simple air-gap transformer can be balanced without any difficulty to a "standard," so as to form a negligible factor in the determination of a satisfactory service fault-setting. The author's advocacy of very low earth-fault settings appears quite attractive at first sight, but I am of the opinion that it cannot be universally applied with advantage, owing to the many other factors which determine the safe setting value, quite irrespective of the capabilities or limitations of the protective apparatus itself, as referred to in the paper. Assuming, however, a given low earth-fault setting to be obtained with stability of the system, the advantages or otherwise must be considered in the light of the following arguments. If the principal advantage of a *low* earth-fault setting on the network is to limit the disturbance or shock on the system, then a correspondingly *high* ohmic value of neutral-earthing resistance is required to limit the fault current to a comparable amount. On the other hand, the principal object in generator protection is to leave unprotected as small a percentage as possible of the generator winding from the neutral point; and as this is governed entirely by the ratio of the fault-current setting to the current passed by the earthing resistance, a *low* ohmic value is needed in this case if any advantage is to be gained by the low fault-setting. Further, the use of an earthing resistance of high ohmic value is dangerous, as the system approaches the condition of an insulated one, and when an earth fault occurs on one phase the other two will be instantaneously subjected to $\sqrt{3}$ times the transient voltage existing during the fault. This very rapid pressure-rise, probably at the resonant frequency of the system, will search out any weak spots in the insulation of the other phases, and experience shows that in actual service such conditions produce simultaneous earth faults on separate phases. In addition to this increased risk to the insulation, faults which are too limited by the earthing resistance may be difficult to locate, and in all probability the procedure of burning them out will be finally resorted to. Is not the better way, therefore, to allow a heavier fault current to pass which will not only be sufficient to burn out and clear the fault in one operation (thus avoiding delay in resuming service) but will also reduce the surge energy on the sound phases and lessen the risk of further failure? Generally speaking, I think that the compromise is in favour of the low-ohmic-value earthing resistance; and it is interesting to note that, whilst the smaller systems are employing a limiting resistance in the neutral, the tendency in the large modern stations is towards solidly earthing the neutral point. A low fault-setting on the network is only obligatory, therefore, if the system is earthed through a high resistance (in order to ensure operation), and this may be accomplished either by the inherent addition of the biasing transformer in the author's scheme or, in the case of existing Merz-Price systems, by the simple addition of a diverter relay. On the other hand it is questionable whether any extra complications are justified in the majority of cases where the current passed by the earthing resistance has been determined upon the lines discussed above, as experience proves that it is often preferable to sacrifice the low fault-setting to simplicity and stability by employing the Merz-Price system in its simplest form. The author describes the occurrence of simultaneous earth faults as being exceptional. He limits his statement, however, to pressures not exceeding 11 000 volts, but I take it that he does not intend to imply that the successful operation of his systems of protection is similarly limited. No system of protection can be successful unless it works satisfactorily under the condition of a straight-through fault which is not limited in value by the neutral earthing resistance. In other words, the setting employed for obtaining stability for an earth fault must be equivalent to that necessary for a fault between phases. By employing solid-core transformers a large unbalance will be caused with a straight-through earth fault of between-phase value, and, in view of the fact that a low earth-fault setting is employed in the author's schemes, I should be glad to know whether stability is assured in this case under service conditions. In the case of generators the fault-setting should be as low as possible, consistent with stability. I should have expected the author to have specially advocated a low fault-setting here, and I should like to know his views upon this point, as no specific reference is made under this heading in the paper. With reference to the author's remarks on page 598, presumably referring to the Merz-Price system, it is not essential for a sheath to be employed on the pilot cables; this is only one of the methods by which capacity currents may be compensated for, and is only used where lower fault-settings are desired. With regard to air-gap transformers, when these are employed there is no possibility of the relays becoming damaged under short-circuit conditions, the danger of which is referred to by the author. All air-gap Merz-Price transformers are carefully balanced to a standard, are completely interchangeable, and during very high currents form a negligible factor in obtaining stability. Incidentally this is much simpler and cheaper than the use of a separate biasing transformer. My remarks above have already shown that the advantage of a low earth-fault setting may be outweighed by other considerations. The Merz-Price system is also stable under conditions of simultaneous earth faults

of between-phase value, probably to a greater degree than the author's alternative. With any form of Merz-Price protection, low fault-setting may be obtained by the employment of the diverter relay, in cases where such additional sensitivity is desirable. Seeing that very low fault-settings are obtained with the existing split-conductor system, I find it difficult to appreciate the necessity for the extra complication proposed by the author. In the case of transformer protection the author proposes to use a d.c. auxiliary restraint which comes into action during the closing of the main switch. I hardly think that this is a solution of the problem, as it makes no provision for current-rushes which occur after the switch has been closed, such current-rushes or surges being due to rapid changes of load under fault conditions. I shall be glad to know whether low fault-settings can be made stable and are recommended by the author under these conditions in service. The being connected to the protective relay and the other to a fault-indicating relay. Overload transformers are also provided for single-line protection. This scheme is exceedingly simple and operates correctly under all conditions of service on a ring main. No auxiliary switch is employed and isolation is positive and depends only upon the value of the current, no potential elements being employed for the tripping operation. As the lines are separated in the form of two cables or otherwise, all faults are either between phases or to earth, and thus complete protection for every operating condition is obtained. If step-up power transformers are employed in the two outgoing lines, then complete protection is afforded to them, both on the high-tension and low-tension sides. Earth-fault indication may also be obtained by providing current transformers for the neutral leads on the secondary side of the step-up transformers. When a fault occurs, both lines are

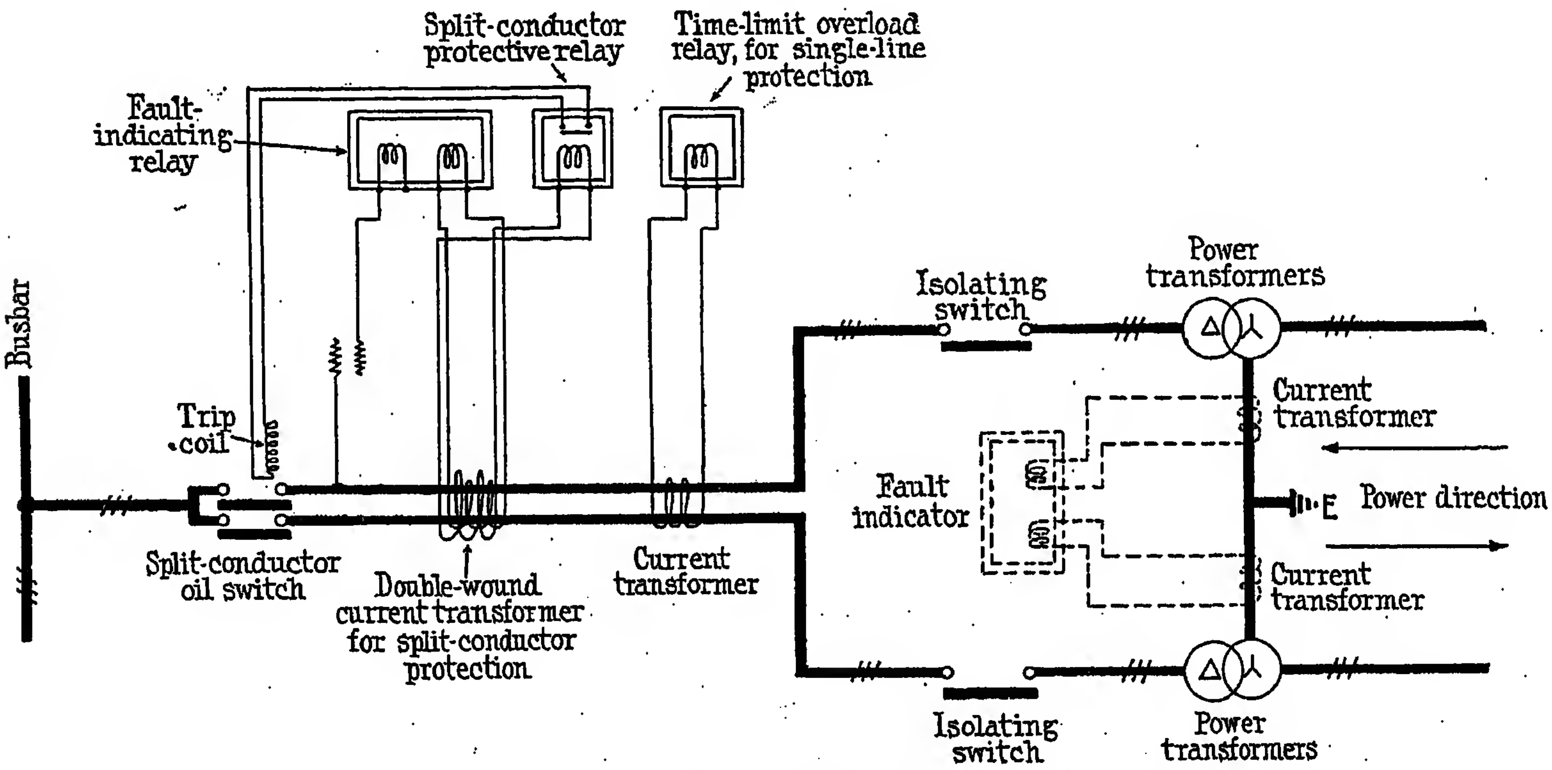

FIG. D.—Split-conductor principle applied to parallel feeders with faulty-line indication.

author applies the principle of the biasing transformer to various forms of parallel-feeder protection. I am not quite clear as to the true advantage of the use of the biasing transformer for such protection, as it only applies to known systems which are admittedly far from ideal. He acknowledges the fundamental difficulties, and in the scheme advocated by him, employing a balanced-power arrangement, no protection would apparently be obtained on simultaneous three-phase short-circuits. The great disability of many of the systems shown is that they are only suitable for a power feed in one direction, which practically debars them from modern networks, where ring mains are more or less essential. The split-conductor principle may be applied to parallel-feeder protection in a very simple manner, and this is shown in Fig. D. The two lines are fed from a standard split-conductor oil circuit-breaker and are passed through standard split-conductor transformers each having two windings, one winding switched out and the indicating relay shows which is the faulty line. The sound line can then be closed in immediately. In view of the complete and positive protection afforded, there is very much to be said in favour of this extremely simple form of protection.

Mr. H. Trencham: Protective gear of the type using pilot wires was first seriously taken up in the North-East district, but its real importance is not yet realized as it should be in many parts of the country. Mr. Clothier touched on a very interesting subject when referring to the new difficulties which occur in adapting pilot-wire protection to high-voltage schemes. In the United States and on the Continent such development has been avoided, but it does not necessarily follow that the subject is entirely intractable. In my opinion the success which has in the past attended the work done in this country augurs well for the successful surmounting of the new difficulties which appear.

Mr. W. A. A. Burgess: It is to be regretted that

the author's efforts have led him away from, rather than towards, that simplicity which is the ideal in the electrical and also every branch of engineering. In looking back upon the process of evolution of the majority of successful engineering products, one can usually trace an original and comparatively simple idea through a maze of complication to a final simplified form still embodying all the advantages towards which the more complicated forms were aimed. To my mind the author's scheme of biasing transformers is still in that complex though useful stage which, while insufficient in itself to meet the aims of those responsible for its development, is still a definite and necessary step towards their ultimate simple fulfilment. The need for certainty of operation under predetermined fault conditions (and there is nowadays no need to go to extremes in sensitiveness in fault settings on a well-designed system) and for equal certainty of non-operation with heavy normal currents is undoubted, but the simplest and soundest way to secure this is surely to improve the design and balance of the main protective current transformers rather than to endeavour to correct errors of bulk manufacture by introducing an additional piece of apparatus to the circuit, even though that additional part be much more simple than that proposed by the author. A case for the improvement of existing forms of apparatus may be instanced where two feeders are provided with "parallel feeder" protection, a very common expedient in modernizing the older networks. Even the author's equivalent of a wireless receiving set replete with fuses will not prevent the healthy feeder from being automatically switched out, nor will it assist him in the quick determination of the faulty line. As an instance of intermediate over-elaboration, I once attempted to apply Merz-Price protection to a three-phase overhead ring main with 12 tees off it, each capable of passing current both into and out of the ring main. The object of the ring main was to equalize the load on ten 0·25 sq. in. low-tension feeders in an industrial works, to save additional copper. The product was a particularly valuable one; the processes involved were continuous and the cost of the protection, if it would work within reasonable limits, was justified. My first inclination was to connect all current-transformer secondaries in series with a ring cable broken at the relay, "star" one end, connect the relay across the other end and join the neutrals to effect the E.M.F. balancing. Next, to reduce the fault setting and still use straight-through current transformers, I investigated current balancing, which appeared to require at least three secondary leads from every current transformer to be brought to a common relay centre, involving a number of very long lengths of pilot cable of relatively heavy section and the possibility of compensating resistances. This was very nearly the author's method and I was frankly appalled at my creation. I next decided to try the effect of paralleling all current-transformer secondaries on a common ring pilot, starring one side. At this stage I obtained the necessary current transformers from Messrs. Reyrolle. A preliminary test proved the system to be workable and it was afterwards found that, using standard 7/21½ S.W.G. 3-core pilot cable, the relay could be put at any point of the ring pilot without affecting its successful operation. The system has now been in commission for 6 years and operates with great promptitude whenever a crane jib fouls the overhead wires or a piece of corrugated iron short-circuits them. The total possible current input to the ring main is about 3 000 amperes, and a motor connection requiring 50 amperes teed off within the protection will operate the relay. In conclusion I should like to advocate the consideration of the application of the balanced-protection idea to the more mechanical side of engineering, to buried gas and water mains and to the indication, at least, of heat leakage and waste all the way from the fuel to the unit of electrical energy. I am sure that no biasing apparatus would be tolerated in that field, and it hardly seems necessary in the field covered by the author.

[The author's reply to this discussion will be found on page 619.]

North Midland Centre, at Leeds, 26 February, 1924.

Mr. W. B. Woodhouse: It would be of interest if the author would give some indication of the cost of the apparatus which he describes in the paper, as compared with that of other forms of protective gear in general use.

Mr. D. M. Buist: When protective gear was first introduced, it was considered to be relatively unimportant. Some supply engineers in those days contended that it was unnecessary to protect against troubles that they never or seldom encountered, while others contended that the remedy was worse than the disease, and in the majority of cases such arguments were unassailable. The first contention has now been refuted, however, chiefly due to the rapid growth in the size of individual undertakings, whilst the second contention has been reversed by the improvements effected in protective gear in recent years. The present paper is indicative more of improvements than of the introduction of new systems. The outstanding feature of the paper, is, of course, its advocacy of what is really a radical departure in the design of protective gear, namely, the use of biased transformers in place of biased relays. This transference of the bias from the relay to the transformer certainly constitutes a notable improvement as it not only permits of the use of a more simple and robust and yet less sensitive relay, but also affords greater overall sensitivity, as this feature is transferred with the bias to the transformer. At the present day, users of protective gear are divided into two schools, those who prefer high settings and those who prefer low settings. I, personally, belong to the former school, preferring to install sensitive relays of the Fawssett-Parry type, not necessarily in every case employing the minimum setting, however, but rather allowing experience of the network and the growth of the undertaking to decide the correct setting. The installation to

which I refer is only in its embryo stage at present, and I fully anticipate that I shall change my opinions with time, but another reason for my choice of such a flexible arrangement, quite apart from the two reasons already given, is that, despite the use of Beard compensated pilots and recent improvements in the transformers, I wish to incur no risks from the presence of triple-frequency currents which recent oscillograph tests have displayed. In point of fact, we are even now seriously considering leaving the secondary circuit unearthed for this reason, as in any case the general practice of earthing at one end only of the secondary circuit is no adequate protection to the operator should he be engaged on the protective gear at the opposite end. The possibility of operation by triple-frequency currents applies to all systems of protection employing leakage relays or earthed-neutral supply systems. I should therefore like to ask the author if he has taken cognizance of this point, particularly as none of his feeder diagrams shows an earth connection in the secondary. I believe I am correct in stating that this paper is the first one on this subject to deal almost entirely with the design of protective gear, or at least to keep design to the forefront throughout. Its value would have been greatly enhanced if the results achieved in practice in those installations referred to in the penultimate paragraph had been described with a detail equal to that displayed throughout the paper. A set of curves showing the comparison between the author's gear and existing systems, from the points of view of tripping current and stability on "through" short-circuits, would also have been valuable, as supply engineers as a body are too busy to digest thoroughly the contents of such a lengthy paper as this is. While on this subject of sensitivity, particularly on feeder protective gear, I should like to ask the author's opinion of the following statement: The more sensitive a setting and therefore the less disastrous the effect of a fault, the more difficult it is to locate the fault. An increase of sensitivity results in tripping the oil switch earlier but, in my opinion, the fraction of time thus saved is negligible. Moreover, as the sensitivity is increased, slight variations in the mechanical time-lag in the operation of the oil switch assume relatively greater importance. An interesting experiment to substantiate or disprove the foregoing contentions would be to apply the author's proposals to a circuit already protected by Merz-Price gear and to carry out a series of tests with varying fault currents, including a dead short-circuit. I think that it will be agreed that the rapid growth of the fault current would reduce the interval of time in passing from a tripping current of, say, 100 amperes for the author's gear to a tripping current of, say, 400 amperes for the ordinary Merz-Price gear, to such an infinitesimal amount that both relays would appear to trip instantaneously. For this same reason I would ask the author if, for stub-ended feeders, combined overload and leakage protection is not equally as efficacious as any system he has put forward, because, after all, it is merely an application of the Wedmore principle.

Mr. M. Wadeson: The less protective apparatus is used the better, and I think that if simple overload protection will suffice that is the best system. It is, I believe, now becoming quite general in large power systems to do away with much of the complicated protective apparatus and use overload protection as far as possible.

[The author's reply to this discussion will be found on page 619.]

North-Western Centre, at Manchester, 4 March, 1924.

Mr. H. A. Ratcliff: The paper deals with apparatus for the protection of alternating-current circuits, and the author frequently refers to protective devices. "Protective" appears to be a misnomer, and a better description would probably be "isolating" or "locating." No form of protective gear protects in the sense that it prevents a fault occurring, although it may be correct to say that it protects other portions of a system from the effects of a fault on the automatically isolated section. The author emphasizes the importance of clearing small earth faults instantaneously, but it is equally, if not more, important that short-circuit faults should be cleared instantaneously. Up to a year or so ago it was the general experience that 99 faults out of every 100 originated as earth faults and as a rule they could be cleared before they developed into short-circuits, but recent experiences in various parts of the country with extra-high-tension cables have indicated that the same sequence of fault development and clearing is not likely to obtain. The real essential in connection with protective gear is discrimination between one circuit and another, and between one portion of a circuit and the remainder of the circuit. That is the principal reason for the design and development of pilot-wire systems of protection. It is possible to attain a certain measure of discrimination by means of time-lags on the relays, but their use should always be avoided where possible. Time-lags on protective gear are always most undesirable, but where there is no possible alternative means of discrimination they are probably the lesser of two evils. The author emphasizes reliability, with which I associate stability. Unfortunately, that is the one feature which much of the so-called protective gear on the market does not possess. As the author clearly shows, the safe operating range which a protective relay has to cover is enormous and is perhaps not always fully appreciated by either manufacturers or users. As mentioned in the paper, the ordinary range of operation for electrical apparatus is perhaps 10 : 1, and in the case of most a.c. instruments it rarely exceeds 5 : 1. Protective apparatus may, however, have to withstand a current-range of 400 : 1, and as the resulting forces usually follow a square law the difficulties incidental to the designs of suitable relays, etc., are very pronounced. With reference to reliability, it is obvious that protective gear must be absolutely above suspicion; otherwise it is worse than useless and merely creates a sense of false security,

which is extremely dangerous. It is therefore unfortunate that much of the gear on the market is flimsy, badly constructed and frequently unreliable. That, perhaps, is not entirely the fault of the manufacturers. It arises from the fact that protective gear when it was first introduced was regarded as a somewhat novel luxury and consequently, in order to create a demand for it, the price was cut and the quality suffered accordingly. It is now realized, however, that protective gear is an absolutely essential requirement of all involved distributing and transmission systems, and consequently there is more inducement to the manufacturer to develop high-grade apparatus. Apart from the relays, the main trouble with protective gear undoubtedly arises from the limitations of the ordinary current transformers, and it is in recognition of these limitations that the air-gap current transformer has been evolved. Admittedly the air-gap type possesses certain advantages, but the outstanding feature of the author's arrangements is the use of closed-iron current transformers instead of the rather delicate air-gap type. This has been rendered possible by the author's biasing scheme. The idea of controlling certain effects by induced magnetic saturation is not novel, but full credit should be given to the author for the development of his ingenious adaptation of it. It would appear that the principal source of trouble on e.h.t. systems, apart from actual breakdowns, is likely to be the comparatively heavy transient current-rushes resulting from switching operations in connection with large transformers or cables having considerable capacity. For example, the normal balanced charging current of an ordinary 33 000-volt 3-core cable at the normal frequency of 50 cycles may be of the order of 2½ amperes per mile, but in the event of one phase becoming earthed the resulting unbalanced capacity current may be of the order of 3½ amperes per mile at normal frequency, and possibly 100 times greater under surge conditions. No doubt the author had these conditions in mind when developing his biasing transformer, and it would therefore be interesting to know to what extent he has succeeded in meeting them. My actual experience of his gear has not been sufficient to justify a definite opinion on its behaviour under the conditions arising from severe transient disturbances on a large e.h.t. three-phase system. The limitations of ring transformers have been referred to in the paper and it is advisable that they should be recognized. There is a tendency nowadays to load single-turn ring transformers with instruments and overload and protective relays, etc., and then to expect the instruments to be accurate and the protective gear to be reliable. Very few instruments are shown in the protective circuits given in the paper. It is certainly inadvisable to have both instruments and protective gear on one transformer. If separate transformers are employed for the protective gear there is undoubtedly a good case for the single-turn type, and within its limitations it is, under such conditions, very satisfactory. Probably the best and simplest arrangement for protecting a power transformer is to use a plain ring transformer having a large window, and to thread all the phase conductors and the neutral conductor through it. This method of employing the simple phase-balance system of protection overcomes the difficulty experienced with separate current transformers in each conductor owing to magnetizing current switching transients. The paper contains many diagrams which will repay careful study, but it is difficult to avoid the conclusion that some of them are unduly complicated, for, after all, as the author states, one of the essential attributes of protective gear is simplicity, and it is rather difficult to associate simplicity with some of the figures. When compounded into tanks with a few terminals on the covers, the biasing transformers do not appear to be unduly elaborate, but the complicated nature of the circuits becomes evident when checking connections or locating troubles. To me the most interesting figure in the paper is Fig. 25, showing the evolution of the feeder protective gear. It indicates very clearly how the scheme has gradually evolved from simple balanced earth-leakage protection to full fault-discriminating and biased protection. It also shows the very important characteristic feature which distinguishes this particular arrangement from other opposed-voltage systems, i.e. the purely local circuit through the biasing transformers at each end of the line. The result of this is that the current transformers are actually loaded instead of being merely voltage transformers, and consequently ordinary standard types having closed magnetic circuits may be employed. The possibilities of the author's biasing system appear to be almost illimitable, and in Fig. 22 a very ingenious compound bias is shown. First, there is the a.c. bias, and then in addition there is a d.c. bias. The arrangement is shown applied to a transformer which it protects throughout, from primary to secondary terminals. No doubt the arrangement is very effective, and it would therefore be interesting to know whether the author considers the scheme to be satisfactory for the overall protection of a generator and step-up transformer. The problem of devising a satisfactory system of overall generator and transformer protection is by no means a simple one. The screened pilot cable has been a necessity with certain types of opposed-voltage gear in order to eliminate or minimize the effect of the capacity currents in the pilot conductors on the relays. Screened pilot cables do not, however, overcome the difficulties incidental to the capacity currents in the main power cables. I should be glad if, in that respect, the author would say to what extent his biasing system will render his gear immune from the effects of heavy current-rushes due to the capacity of the main cables, and also whether the gear gives immunity from the effects of triple-harmonic currents. The comparison between a.c. and d.c. relays is very interesting. Most of the latter, of course, follow a square law and the pull increases enormously as the gap in the magnetic circuit closes. With a.c. relays, unfortunately, there is frequently more or less of a floating effect, and consequently in certain cases they are apt to be unreliable. The difference in the operating forces with the two types is very clearly shown in the paper. The resonant a.c. relay is both interesting and ingenious. I am more particularly interested in the possibilities of the device for overcoming the difficulties experienced with certain forms of protective apparatus due to transient effects.

On a somewhat similar scheme being proposed recently it was condemned for the very reason which the author recommends. The author would be well advised to limit his various protective schemes to arrangements employing current transformers only, since extended experience has shown that protective schemes which necessitate the use of potential transformers are unreliable.

Mr. H. Pearce: The separation of earth faults from line faults, referred to in the paper, is a procedure which is not supported in every quarter, but I think that there is a growing tendency to realize that earth faults must be provided with a low setting because of the limitation to the fault current by the neutral resistance. This limitation does not apply to the line faults—faults between phases—and there is therefore no reason for limiting the setting of these relays to such a low value. In the early days of protective gear many troubles occurred due to the earthing resistance not being rated at a sufficiently large current. For this reason I would urge designers of protective gear to insist upon having ample current to operate the relays. In the case of certain installations carried out some years ago difficulties occurred in this direction. The gear had been installed for some time and under such conditions that it could not possibly operate, yet this was only discovered after several breakdowns of expensive plant had actually occurred, so that the operating engineers had been under a false sense of security until the actual troubles developed. This leads me to mention the importance of testing protective gear on site. The tests should be carried out by the application of actual fault current to the primary conductors without disturbing the secondary connections. This is not merely a refinement; the secondary connections require to be tested as much as any other part of the protective gear. Manufacturers are able to produce protective gear which will meet, very largely, even the severe requirements of the large systems of the present day; but it is not sufficient to design and construct gear which will operate when first installed. To obtain satisfactory service it is necessary for the gear to be maintained to the same extent as any other part of the power equipment. Unfortunately, the tendency is to maintain all the important pieces of plant very efficiently but to ignore some of the less important items—the items which do not actually produce revenue—and protective gear in the past has definitely suffered on this account. The two main objects in installing protective gear are to limit the damage to expensive plant on the occurrence of faults and to localize the disturbance by preventing healthy circuits from being cut out when faults occur in other parts of the system. If it is worth while paying for apparatus to fulfil these functions, it is equally worth while to spend care and attention in testing and inspecting the equipment at regular intervals to ensure that it carries out the functions for which it is installed. It is only by the supply engineers co-operating with the manufacturers that we can arrive at the best results from protective gear, as with any other piece of apparatus. Furthermore, no branch of engineering can advance adequately until detailed facts are carefully scheduled, tabulated and analysed. For these and other reasons protective gear, when installed, should pass through acceptance trials in just the same way as any other piece of apparatus.

Mr. G. A. Cheetham: Many years ago I experimented with a biased relay and decided that it was not a piece of apparatus to put in a protective circuit. The author appears to have overcome the difficulty by including the biasing in the transformer. In the old days the necessity for biasing relays arose due to the difficulty of balancing transformers. I suggest that this difficulty is practically non-existent at the present time. There are many protective systems now in operation which depend purely upon balanced transformers and give excellent results. I know of a system in which generators of a large capacity are operating and feeding two substations in series through feeders protected on the balanced-voltage system, the generators themselves being protected by the ordinary Merz-Price circulating-current system. When a dead short-circuit occurred on the busbars of the second station, which was outside the protected area, the pressure on the main busbars in the generating station was reduced from 6 000 to 2 000 volts, indicating the severity of the fault. None of the protective relays tripped, indicating that, under those conditions, the balancing of the transformers was quite good. I may say that it is possible to have stability on generators, and, with a slight modification of the Merz-Price circulating-current system, it is possible to protect 92 per cent of the generator winding with an earthing resistance which on a dead fault (phase to earth) will allow full-load current to pass. With the Merz-Price system it is not possible to protect quite so much of the winding, but many generators in the country are working with the Merz-Price connections and obtaining excellent results. We have had many examples of short-circuits on the generator with the protective gear not operating under the conditions of a straight-through fault when, of course, it should not operate, which proves good transformer-balancing. The author gives some tentative figures, but he suggests that it is possible to get less than 10 per cent setting on the relay. I suggest that it is possible with the system mentioned above to get less than 10 per cent. If self-balancing is applied to the generator the operating current is, of course, a definite quantity. It is possible to obtain a setting with stability of 50 amperes, and on a high-capacity machine this represents a very large percentage of the winding protected. Generator reactance limits the short-circuit current to reasonable values, but on feeder circuits the short-circuit current varies very much according to the capacity of the feeder. In this case it is obvious that the smaller the capacity of the feeder the higher is the fault current compared with the normal capacity of the feeder, and therefore it is possible to set the relays much higher on a feeder with safety, provided the gear acts quickly, and I do not think that there should be any argument on that score. It has been proved in practice that, provided the fault is cleared quickly, very little damage is done to the apparatus which the gear protects. I wish to emphasize this point as in my opinion it is an important factor;

I have seen breakdowns in which the resulting damage was a mere pinhole. On page 568 the author instances a case where there is no current on the one feeder and a current on the other, and under those conditions the relay is operating without restraint. In the previous section he says that the relay would receive only a limited current no matter how severe the fault might be. I should be glad if the author would explain these apparently conflicting statements. Except in its application in this particular instance, has the author used in practice the method of d.c. control suggested on page 573, and, if so, for what purpose? I know it has been used on the Continent, but I have never seen any results of its operation. With reference to the relay section of the paper, it has never been our practice to use this augmented-contact system on a relay. We have preferred to use a "drop switch," and this has found increasing favour with supply engineers. It has the advantage that it definitely locates the fault. The operator has to go to the relay to reset it by hand, and he is therefore bound to know where the fault has occurred. The phantom system of auxiliary switch,

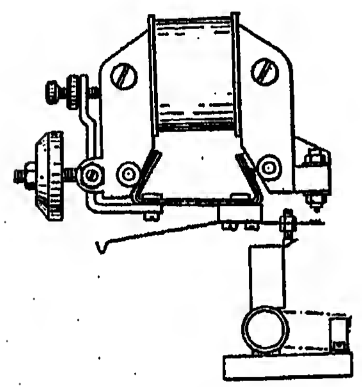

FIG. E.

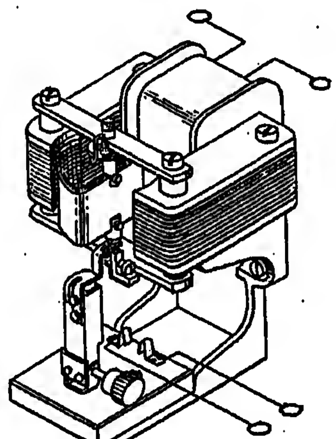

FIG. F.

which is suggested in the paper, is particularly neat, but it seems to me that it is largely a makeshift where one is forced to provide something because one cannot get auxiliary switches on the oil switch. On page 579 the author suggests a scheme for the adequate protection of a transformer, but of course he is disturbed by the transient currents which occur during switching. That is a common difficulty, which in the past has led to very high settings for protective apparatus for transformers. Some time ago a system was designed in which during switching operations a fuse was inserted across the relay winding for the purpose of temporarily raising the setting. This worked very well indeed. The author objects to air-gap transformers for feeder protection, but I am very strongly in favour of air-gap transformers with a straight-line characteristic. I have had excellent results with those transformers and I see no reason why their use should be discontinued. Of course, one is faced with the problem of increasing the sensitivity of the relay. This appears to me to be more an imaginary than a real difficulty. People seem to conclude that when a relay is made sensitive it is a very unstable piece of apparatus. Figs. E and F indicate how a relay can be made more sensitive without reducing its stability. Fig. E represents an ordinarily constructed armature relay using a conventional form of drop-switch attachment. There is an ordinary magnetic circuit excited from a single coil, and the attracted armature is balanced with a flat balance weight. There is also a mechanically latched drop-switch which descends by gravity and completes the tripping circuit. This relay, when designed some years ago, was considered to be fairly sensitive, as on 50 periods it operated with about 0·15 volt-ampere. To meet the demands of the balanced-voltage protective gear it was decided that a more sensitive type of relay should be used. The relay was, therefore, modified in the following way, as shown in Fig. F. Practically the same iron circuit was used as in the first case, except that the air-gap at the bottom was curved to allow an iron piece to swing in the centre. It was seen, of course, that in order to balance the relay in the original design and obtain the necessary setting, more weight had to be added to the pivots instead of balancing the armature itself. In the figure the armature itself is balanced, and furthermore it swings on a footstep bearing which reduces the friction considerably. The same drop-switch was used. A friction wheel was introduced and an ordinary strut was brought out from the relay shaft, which simply held the drop-switch. When the winding is excited it pulls the armature round. The results of these modifications of design reduced the necessary actuating force from 0·15 to 0·005 volt-ampere. The relay was quite stable, and has been found to give very good results on the balanced-voltage protective scheme.

Mr. O. Howarth: In regard to d.c. restraint in the case of transformer protection, such as is shown in Fig. 22, I should like to know whether there is any trouble due to the building-up period required for the direct current. Obviously, the flux does not appear absolutely instantaneously, and the period will depend upon the relative time for the flux to build up and the switch to close. Again, in the case of the phantom auxiliary switch closing the d.c. circuit in order to short-circuit the secondary of the current transformer, the switch which opens and closes that d.c. circuit is liable to have heavy duty, and possibly some trouble may occur if the switch is not good enough for an inductive circuit. In the case of feeder protection, has the author considered the incorporation of a tee off a feeder? I believe it has been done in Merz-Price protection, so that when any fault occurs the three switches come out. A statement is made on page 580 that sensitive line-fault settings are not required for feeder protection. If the protection is carried over feeder and transformer, as is done in many cases, then sensitive line-fault settings are required. Of course, the makers prefer to install the extra apparatus and put separate protective gear on the transformer and the feeder, but if overall protection can be installed it involves less apparatus and less expense. That is more important to supply authorities than to manufacturers. In Fig. 27 one end of the feeder protective cable is shown, the operating winding for the earth leakage being taken from the centre of the overload restraining winding on the earth-leakage transformer. Does the author find it necessary, when he adopts the construction shown in

Fig. 1 (*c*), to use two separate restraining windings connected in series; and does he take the tapping from the connection from one to the other? The reason for my question is that if the tapping is taken from the connection from one limb to the other, then that restraining winding will operate under some circumstances as an operating winding. I notice that in Fig. 41 the author short-circuits the transformers on the feeder which is put out of action by means of a switch which short-circuits the two outer current transformers. Is that quite satisfactory? Is the impedance of the circuits to the mid-point, as picked out in the biasing transformers, low enough to allow of that being safely done? In referring to Fig. 44 the author says that the potential transformer has only half the load on it compared with the arrangement shown in Fig. 43. I should have thought that it would have been rather more than half the load because it has two relays to supply, although it does not supply two potential biasing transformers. If it does bring the load down to half, it suggests that the biasing transformers put a rather large load on the potential transformer as compared with the relays. The author makes a point of the simplicity of the external wiring, but I am not sure that much is gained by boxing-in the complications, as a mistake is very troublesome to locate. One of the principal reasons for the installation of protective gear is to prevent failure of the supply. Most modern transformers and generators are built to withstand short-circuits. Makers of protective gear do not, I think, always sufficiently realize that the essential thing is to clear the fault quickly before the rest of the system has been shut down, as will be the case if the voltage at the busbars falls to a low value and remains low for more than a second. Mr. Pearce referred to the testing of protective gear after it has been installed and the last secondary connection has been put on. The idea seems attractive, but one does not like to put artificial faults on a big high-tension system, because they are liable to be as destructive as the real ones. It does seem to me that if protective apparatus is thoroughly tested out we ought to be able to rely on its correct installation and its accurate operation without running risks with our supply systems. In conclusion, the paper describes what is an undoubted step forward towards 100 per cent perfection.

Mr. S. Ferguson: The figures in the paper exclude the connections between the relays, tripping supply and oil-switch trip coils. These connections are well understood, but I wish to indicate how increased reliability may be obtained by the elimination of the relays and these various auxiliaries. Relays and separate tripping supplies are looked upon as necessary evils; they introduce complications in the wiring on the control board and also many weak links in the chain of connections, the breaking of any one of which will render the protective gear inoperative. Fig. G shows the scheme of connections including relay and auxiliaries, whilst Fig. H indicates a scheme of connections possible with a super-sensitive tripping device, which is now available. In Fig. G the first source of weakness is the tripping battery or independent supply. In the majority of substations, primary batteries have to be relied upon and are very expensive to maintain, requiring constant attention. In generating stations a source of supply which is in some way or other dependent on the main busbar voltage is frequently relied upon. This is unsatisfactory, because when a severe fault comes on the system the pressure is likely to drop and there is not the requisite potential to trip the breaker. The second source of weakness is the fuses, which are necessary if the supply is any other

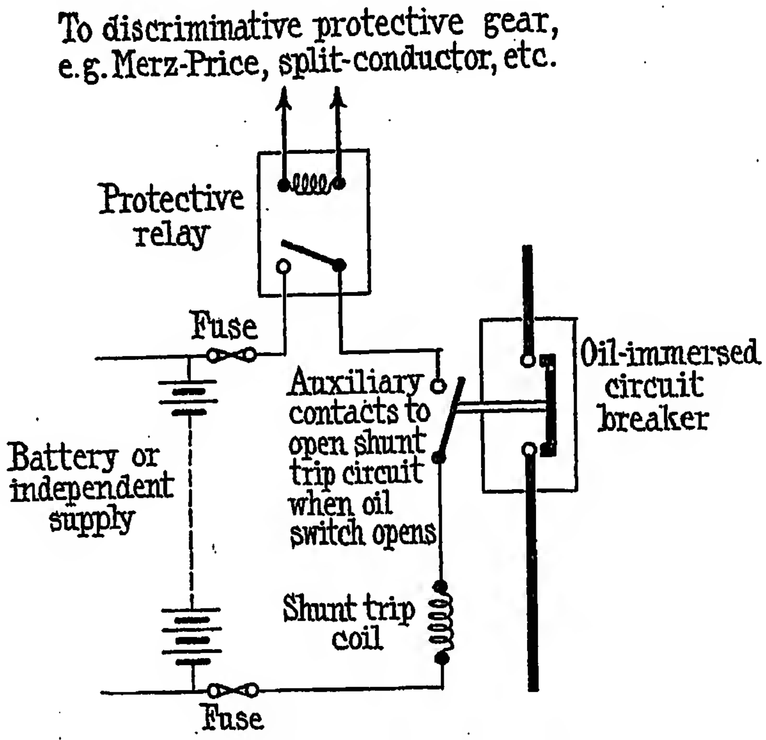

FIG. G.—Connections with relay.

than a primary battery. It is well known that these small fuses do not receive the attention which their connection in such an important circuit merits. The next source of weakness is the auxiliary contacts on the breaker and relay. These are usually very light in construction and can easily fail to make proper contact. This is especially so if a low-voltage supply is used for tripping, as a little dirt between the contacts will break the tripping circuit. The next source of weakness

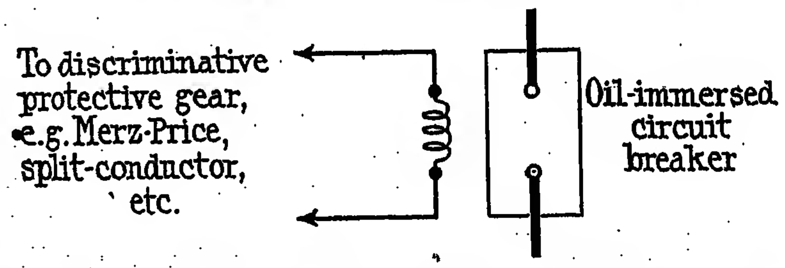

FIG. H.—Connections without relay but with supersensitive tripping device.

is the shunt trip coil. This is usually designed to withstand the pressure of the tripping supply only momentarily. If for any reason it is maintained for too long a period it will burn out and break the tripping circuit. It will be seen from the above that there are five weak links in the chain of connections, any of which might fail and render the protective gear inoperative. I am convinced that fully 50 per cent of the failures of protective gear are due to one or other of these weak links in the tripping circuit. The simplified scheme shown in Fig. H is accomplished by employing a super-

sensitive trip coil, which is as sensitive as any of the ordinary standard relays. This trip coil takes the place of the relay and is operated by the fault current direct. The basic principle of the design is that when the breaker is being closed, either by hand or electrically, sufficient mechanical energy is stored to trip out the breaker when required. All that the fault current has to do is to release this stored energy. It is found that a current of 25 amperes through a ring-type current transformer is sufficient for this purpose. Very few systems adopt lower fault-settings than 25 amperes. It should be noted that the work to be done by the fault current is a constant quantity and not variable with the size of breaker, as it has merely to release a definite amount of stored energy and this is made sufficient for tripping any size of breaker. I believe that in the future the tendency will be to eliminate the complications indicated in the schemes employing relays and adopt the simple tripping arrangement, as it is merely a mechanical problem which has now been satisfactorily solved. It is quite possible to construct the device so that it is perfectly stable even when subjected to considerable vibration. I am pleased to note that biasing can now be embodied in the transformers and not in the relays, as it renders possible the use of the above-mentioned simple tripping device. I feel, however, that biasing is only justifiable, if at all, on a few of the very large systems. It would certainly not be advisable to apply it to the numerous cases which the author has cited.

Mr. T. W. Ross: It is not so many years ago since protective gear was looked upon by nearly all engineers as a nuisance. I think that nowadays, however, their views have changed, and anything which can improve the design of protective gear is always acceptable both to the manufacturer and to the operating engineer. I am surprised that the author experiences no trouble with the internal balance of the biasing transformers. When balancing current transformers my experience has been that if any joints are introduced into the laminated iron circuit, or if the windings are not symmetrically placed round the core, internal balancing troubles always ensue. The author says that, owing to the small size of the transformer, internal balancing troubles are eliminated, and I should be glad of some information on this point. If biasing is necessary for the protection of generators—and I do not admit that it is necessary—it seems to me that the introduction of such a transformer for this purpose, unless it is very carefully built, may be a source of more trouble than that which it is supposed to remedy. Designers of machines are always asking for more sensitive protective gear to protect the windings much closer to the neutral point, but my experience has been that protective gear with a setting which will protect 85 per cent of the winding is quite satisfactory. If that is so then there is no need for biasing, because stability is assured with a suitably designed relay and a balanced secondary circuit. On page 585 there is a series of diagrams showing the evolution of the application of the principle of earth faults and line faults to the protection of feeders. Of course the final result is really a core-balance protection with the addition of line-fault or short-circuit protection. My experience of core-balance protection is that three similar carefully-built current transformers—and by that I mean that each transformer has the same amount of iron in it—will balance correctly, provided no great impedance is added to the circulating-current portion of the circuit. In order to get short-circuit protection the author introduces an impedance into the circulating-current portion of the circuit. He admits that it is necessary to balance the current transformers, but this impedance will upset the balance. I realize that there is a similar impedance at the other end of the feeder which should counteract any such out-of-balance, but I am inclined to think that the unbalanced currents may be out of phase with each other and may give rise to trouble at comparatively small overloads. The author will, of course, answer that the biasing transformer will overcome this, but if the gear becomes unbalanced at comparatively small overloads the biasing will not have any great effect. The suggestion of using a biasing transformer as a means of providing directional protection is very ingenious. I have not studied the diagrams very closely but I should say that the scheme has decided limitations. It seems to me that if directional features are going to be used, a dynamometer or induction relay will be essential. I regret that no mention has been made of the induction relay which has found very great favour in the United States and has also had considerable success in this country. Such relays can be designed to operate successfully at very low voltages, say 3 per cent of normal, at 5 to 10 per cent of normal power. If a current element is added it is possible to have a relay very nearly approaching a directional current relay. With such an instrument protection can be provided for parallel feeders, ring mains, or any other combination of network with a discrimination which, if not so perfect as that in the case of the differential system, is much better than that given by plain overload and leakage protection. The author mentions that his directional relay could be arranged to trip out on very heavy loads with forward power. That, I consider, is a disadvantage, as all discriminating properties are immediately lost. I believe that Col. Edgcumbe tried that feature some years ago in his relay, but he abandoned it as it gave trouble on power networks. On page 585 the author suggests that a biasing transformer could be inserted in the secondary circuit of the ordinary split-conductor transformer. As the output of such a transformer is usually limited it would be difficult to obtain sufficient current to energize a relay from a biasing transformer, and apparently the author prefers the scheme shown on pages 586 and 587. In this arrangement there are two biasing cores in addition to the split-conductor core. To my mind this is a disadvantage, as two other transformers which, of necessity, must be balanced are added to the split-conductor transformer in which no balancing is necessary. The author admits that it is more difficult to balance two magnetic circuits than one magnetic circuit, but in this scheme he resorts to the former practice to overcome something which, as my experience shows, does not exist. With a simple split-conductor system having settings of 50 to 70 amperes the stability is perfectly good, and I know that

such systems are quite reliable in practice. I should be glad if the author would indicate what fault settings he recommends for the different systems which he describes.

Mr. F. Clegg (*communicated*): Referring to Fig. 11, it is unfortunate that it is necessary to connect such a weak link as a potential transformer to the busbars of the station, which presumably are not protected. The author himself confirms this on page 594. I think that everyone will agree with the author's remarks on page 574; in fact it is better to have only protective transformers on the main lines of the system and to avoid meter transformers. I am also in agreement with the author that, particularly for large power systems, the only type of transformer which it is safe to use is the straight-through ring type. On page 580 the author refers to troubles which are due to stray-field effects. I should like to ask him whether he has experienced trouble due to induced currents in the pilot wires when neighbouring conductors are passing large transient fault currents, as he makes a point of employing sensitive settings. This trouble has, I believe, been experienced on systems where the plant capacity has been increased and it has been found necessary to raise the fault settings. On page 598 the author refers to an important point regarding the protection of generators. I think it should be recognized that the minimum setting of the relay on the largest generator generally determines the limiting value of the fault current to earth. In other words it determines the current-carrying capacity of the neutral earthing circuits, i.e. when the system is equipped with discriminative protective gear. I should like to ask the author to what extent results have been affected when the circuit breakers have been provided with buffer resistances designed to prevent current-rushes when switching in. I am, of course, aware that this is no remedy for sudden changes of voltage when the transformers are in commission, as the buffer resistances are short-circuited when the oil switches are closed, but this would also appear to apply to the use of hand switches and other devices for introducing a time-lag at the instant of switching-in the transformer and the subsequent automatic removal of this time-lag. In connection with Fig. 34, the author advocates biasing windings on split-conductor transformers. I should like to ask him whether any actual test has been carried out by passing heavy currents through the transformer, and whether he found the arrangement suitable. On page 577, referring to Fig. 20, which shows the application of phantom auxiliary switches, the idea of changing the impedance of a coil in the ratio of about 1 : 250 is undoubtedly very ingenious and should enable a number of auxiliary switches to be eliminated. It also ensures simultaneous operation in the case of three-phase switches. It should, however, be remembered that there is still in the d.c. control winding one auxiliary switch, the failure of which would nullify all that has been gained. In conclusion, I should also like to ask the author what will happen when the d.c. supply fails. Apparently the set of parallel feeders will be brought out.

[The author's reply to this discussion will be found on page 619.]

Scottish Centre, at Edinburgh, 11 March, 1924.

Mr. C. W. Marshall: In my opinion, the biasing current transformer is the most promising invention for the improvement of standard balanced protective systems that has yet been made public. I think, however, that it is imperative that independent tests of the stability and sensitiveness of these, and of all other protective systems, should be made. The author makes so light of the question of balance that it would appear to be possible to use almost any kind of current transformer for Merz-Price work, provided that the system was supplemented by a balancing transformer. It is obvious that the best results could be obtained by using the balancing transformer to the smallest possible extent. Several speakers in the discussion have stated their objections to protective gear in any shape or form, but anyone who has had extensive operation experience on a large system must realize that continuity of supply cannot possibly be maintained on an interconnected system without discriminative protection. Until such times as we can obtain plant, switches and cables immune from faults, protective gear is a necessity, and it really lies with the manufacturers to get rid of the very bad reputation which they have gained by selling protective apparatus that is not suitable for the conditions under which it operates. So far as I have observed, none of the large manufacturers has adequate plant for testing protective gear under short-circuit conditions. The author states that protective gear must be stable up to 200 times full load, but in the special case of the delta-star transformer, standard Merz-Price circulating-current gear supplied for its protection is unstable at less than 10 times full load. The experience with protective gear on the system of the Glasgow Corporation Electricity Department has established the following facts:—

(1) *Alternator protection.*—Complete stability can be obtained with relays set to operate at 30 per cent of full-load current.

(2) *Combined alternators and step-up transformers.*—Merz-Price circulating-current gear cannot be safely set below 50 per cent of full-load current, and the relays must be used in conjunction with parallel fuses if immunity from tripping, due to straight-through currents, is to be obtained.

(3) *Merz-Price balanced-voltage systems.*—The minimum permissible fault setting on feeders protected in this way is 100 per cent.

(4) *Split-conductor protection.*—It was found that the first setting adopted, viz. 15 per cent of full load, was too sensitive. Several faults were cleared with success before they had developed between phases; in such cases the

> discriminative action of the protective gear is perfect. Even with this setting, however, faults occasionally seem to start between phases, and considerable trouble was caused on account of the opening of split-conductor cables due to straight-through currents. It has therefore been necessary to set up the split-conductor protection to 50 per cent of full load.

The conditions prevailing in Glasgow are such that the maximum possible current on the 20 000-volt system is approximately 20 000 amperes, and on the 6 600-volt system 60 000 amperes (R.M.S. values). On the Glasgow system there are 15 alternators, all protected on the Merz-Price circulating-current system; 78 split-conductor feeders; 78 feeders protected on the Merz-Price system; and 252 transformers. All these cables and machines are concentrated in such a small area that a fault on any one piece of apparatus inevitably affects all the others, and it is absolutely imperative that any fault should be cleared with the minimum delay. In the past 6 years the protective relays have been called on to clear an average of 6 faults per annum, and, except for a few instances of defective stability, the action of the gear has been fairly satisfactory. The Glasgow Corporation has no cause to regret the installation of protective gear, in spite of its weaknesses, but every step towards complete stability without undue loss of sensitiveness will be very welcome.

Mr. D. Martin: The author states in the summary to the paper that biased systems have established themselves and are accepted as being superior to any other, but "any other" includes the Merz-Price and split-conductor systems. The author is obviously a follower of Mr. Wedmore, and mentions his name nine times to the exclusion of others, but does not that prejudice his case somewhat? His scheme throughout seems to be that of adding an additional transformer winding to all the previous well-known systems for the purpose of obtaining an electrical bias. That appears to sum up what may be termed all the original matter in his contribution. In so many words it is an alternative to biasing by relays, such as is done in the McColl system. Fundamentally, therefore, it is not a departure from the already tried systems, but rather the addition of a complication to them. Is that desirable? I have no experience of the new biased transformer arrrangement, but my experience of the Merz-Price, split-conductor and other systems is such as to lead me to hope that development might be along lines which would retain the simplicity of those older and well-tried systems. It is remarkable to note that these older systems have withstood and still survive the onslaught of numerous attacks and improvements to the original patents. Indeed it is difficult to foresee at present on what lines improvement can take place without utilizing the well-known characteristic of the Merz-Price invention fundamental to all protective systems. That leads me to suggest the ideal upon which development should take place: (1) The elimination or a reduction of the number of pilot wires; (2) the elimination of all unnecessary parts and connections, i.e. simplicity; (3) to be as equally sensitive to faults to earth as to faults between phases; (4) stability against heavy straight-through overloads; (5) stability under all working conditions, such as switching on to static transformers using heavy magnetizing currents; (6) interchangeability of the protective transformers; (7) relays to be simple and robust. The split-conductor system eliminated pilot wires, but there was a little difficulty in balancing short lengths of feeders, which affected the stability under heavy straight-through overloads, otherwise it is the ideal for long feeders and satisfies all the above conditions, and is much preferable to parallel feeders under working conditions. If extremely sensitive setting is desired (and that is still a matter of opinion) then the following simple arrangement is available. Mr. Biles of Messrs. Reyrolle has brought out a diverter relay system in which only two pilot wires are necessary (see Fig. A on page 601). This diverter relay does not interfere with the fault setting of the relay until the straight-through current reaches a dangerous limit, at which the diverter relay operates, bringing into circuit an operating relay which latter remains insensitive to heavy straight-through currents but still remains sensitive to fault currents. This system, while it involves the use of an additional relay, is thus simpler and more reliable or stable than any biased type can ever hope to be. Then there is the Fawssett-Parry relay of the sensitive dynamometer type with inertia to avoid inadvertent operation on impulses.

Mr. E. Seddon: We in Edinburgh have decided to adopt this system of protection for the main trunk feeders between Portobello station and the principal substations on the system. We waited some considerable time before adopting any leakage protective gear on these cables, and after looking into a number of other forms of parallel-feeder protective gear we came to the conclusion that the method advocated by the author was the best pilotless system developed up to the present time. To my mind the biasing principle is the basis of all good protective gear. Whether the bias is in the beam relay as in the McColl system, or in the biased transformer, the result appears to be the same, except that with the biased transformer a simple form of relay can be used. Before deciding to adopt this system, a temporary set of transformers and relays was connected to protect the cables between Portobello and Cowgate substation. Definite faults to earth and between phases were made on the e.h.t. side. These tests proved that the gear was in every way satisfactory, and orders were placed for the protection of three sets of three parallel feeders and two sets of two parallel feeders. All the apparatus is now installed, and we shall shortly make further tests on all this gear by introducing definite faults. The fact that the author's biasing transformer is buried in compound will be appreciated by engineers, as it will thus withstand considerable abuse.

Dr. S. Parker Smith: I do not regard protective gear with favour, and I think that it is a pity that it has to be used, but just at the present time it seems to be an unfortunate necessity. In what way is protection to be afforded when a turbo-alternator loses its exciting current, i.e. when the exciter fails? It seems to me that this is a time when protection is necessary, although

as a machine designer I should like to think that my machine would be perfectly safe even under these conditions.

Mr. H. Trencham: The time spent on the work covered by this paper has been about four years and a careful survey has been made of protection in general, with the object of getting down to fundamentals and evolving something in the way of standardization of protective gear so as to eliminate much of the uncertainty which exists at the present day in regard to the functioning of the apparatus. I should like to say a word in regard to protective gear in general. From time to time one or two criticisms have been levelled against us merely because of the fact that we have dealt with other systems as well as with the Merz-Price or circulating-current systems which may be regarded as peculiar to this country—but it should be remembered that in other countries there are electrical power schemes of quite considerable size in which Merz-Price gear has never been heard of, and one has also to bear in mind that very frequently the idea of protection never enters the heads of the engineers handling a job until they are in trouble and until they have got the system into such a state that it is impossible to apply ideal protective gear conditions, and it becomes necessary to do, not what one would, but what one can, and hence we feel that in dealing with the subject at all we must deal with it as particularly as possible and apply our methods to every scheme of protection which has shown intrinsic merit.

Mr. F. E. Meade: The object of all protective devices is to ensure continuity of supply. Different parts of a system such as the generators, feeders, distributors and service mains require different methods of protection because the conditions under which they should be switched out of circuit are not the same in each case. Only consumers' service mains call for automatic devices actuated simply by overload conditions. Overload protection in interconnected systems, and particularly in generator circuits, is simply conducive to total shut-down, and the design of apparatus should be such that it is proof against damage from overload. The criterion of a fault in a generator working in parallel with others is that the machine is no longer supplying power to the busbars. Generator trouble may be due to the failure of the steam supply, a breakdown between the terminals of one phase, breakdown between phases, and failure of the exciting current. The first two faults involve a reversal of power, but neither the current-balancing nor the split-conductor system gives protection unless a fault on one of the phases develops into a breakdown between phases. Failure of the excitation on one machine does not result in a reversal of power unless this machine drops out of step, and the gear described in the paper would not operate until this takes place. Has any adequate system of guarding against this contingency been evolved or been found necessary? The author's application of the biasing transformer should add greatly to the effectiveness of the current-balancing system for generators and transformers where low values of fault settings are desirable. It may be pointed out that with the ordinary arrangement of balanced transformers where the natural circulating current flows in the secondaries, contrary to the statement on page 565, ordinary current transformers may be used and measuring instruments included in the secondary circuit. The greatest care must of course be taken that the points across which the relay is connected are suitably chosen (see Fig. 3). It is in connection with the opposed-voltage protective system for feeders that the advantages of the addition of the biasing transformer are most clearly seen. Hitherto the trouble due to saturation in the transformer cores and consequent difference in the induced voltages has been avoided at the expense of decreased sensitivity. On the occurrence of a short-circuit on other parts of the system, perfectly healthy feeder sections may be called upon to carry enormous currents for a short time. Even if the transformers are perfectly balanced, the large E.M.F. induced gives rise to capacity currents in the pilot wires. Unless the fault setting of the relay is made high, these may cause it to operate and disconnect the sound feeder. The use of the biasing transformer avoids the additional cost of compensated pilot cable, and accurate balancing of the air-core transformers is unnecessary in order to secure immunity from incorrect tripping under these severe conditions. The author's statement that the balanced-voltage protection will be used in the future more extensively than the split-conductor system which on some power schemes is superseding the former, will probably be challenged. The elimination of pilot wires is of such importance that the difficulty of obtaining equal impedance in the two halves of the split conductor when joints are made is relatively a minor one. To obtain sensitivity the split must be carried through the switch. Can the author say if any development of his system is likely to result in the split switch being unnecessary?

[The author's reply to this discussion will be found on page 619.]

South Midland Centre, at Birmingham, 30 April, 1924.

Mr. F. Forrest: The simplicity and reliability of the circulating-current protective system as applied to alternating-current generators has been amply demonstrated over a number of years, and many of us thought that we had reached something like finality in this matter. I am not satisfied that the application of biasing transformers to circulating-current protective circuits is justified. It undoubtedly adds to the complication and introduces a number of additional circuits and connections, the failure of any one of which would lead to trouble. It is of the utmost importance that all relays and protective apparatus in connection with a.c. generators and feeders should be regularly and systematically tested for correct operation, and especially is this the case where the relays operate with almost minute forces. The arrangement shown in Fig. 22 seems very complicated and would be rendered unnecessary if all transformers were switched in through a charging

resistance capable of passing, say, 10 per cent more than the magnetizing current. These charging resistances are coming more and more into use, and serve the double purpose of reducing the current-rush at the moment of switching in and the building-up of potential between the end turns, which is such a fruitful cause of breakdown. The satisfactory protection of parallel a.c. feeders is still one of our biggest problems, and it is questionable whether in many instances it is wise to couple such feeders in parallel at the substation end. If the substation busbars can be sectionalized and the load adjusted, as it usually can be, to suit the capacity of the feeders, there is very little to be gained by connecting the feeders in parallel, whilst the arrangement of running isolated feeders has much to commend it, especially on a big system.

Mr. W. Wilson: There is much in the paper with which we should all agree. In the first place, few people now question the value of protection for alternating-current circuits and apparatus. The restriction of the damage to a trivial amount consequent upon a breakdown of the installation, and the localization of the trouble to the particular section in which it originated, are such valuable results that the comparatively small outlay entailed by the installation of protective gear becomes an extremely cheap form of insurance. I was recently able to inspect a portion of a feeder which had sustained a short-circuit. Thanks to the balanced protective gear the damage was restricted to a small metallic bead not much larger than a pin's head, requiring in the present instance only a very small amount of attention to repair it. This should be compared with the extensive damage that is usually sustained by unprotected lines or apparatus when a breakdown occurs. For example, a turbo-alternator of, say, 6 000 kVA, or above, can be, and usually is, completely burnt out in a space of about 10 seconds following the development of a fault in the stator windings. The author's case in favour of biased protection is also a strong one. The protective gear must be designed to give satisfactory operation under the extreme conditions that are likely to occur in practice, and these are represented by the occurrence of a dead short-circuit beyond the current transformers, permitting the passage of something in the vicinity of 20 times the normal full-load value of the current. In this event any slight error of balance that exists or can develop on overload in the current transformers is multiplied by the same factor of 20; and if the relay is set to trip at a comparatively small percentage of the normal full-load value, and is not rendered less sensitive at higher loadings by the application of a bias, the magnified error is sufficient to trip it at a time when there is no fault in the circuit to be protected.* For this reason unbiased systems require very high settings to prevent them from operating incorrectly upon overloads, but are thereby rendered very insensitive under ordinary conditions. The "resonant" relay shown in Fig. 17 with a capacity method for increasing the power factor of the winding is, in particular, an interesting proposal for overcoming a difficult problem. There are, however, a number of respects in which I cannot help differing from the opinions which have been expressed. On page 562 it is stated that "difficulty is met with in designing biased relays in forms sufficiently sensitive to be operated by the limited energy available, on account of the considerable force which they must withstand without operating." This is an unfavourable criticism of existing biased relays that in my experience is far from being justified. If it be supposed that the "limited energy" is derived from the smallest current transformer used in practice, viz. the 40 VA pattern, as employed for switchboard ammeters, etc., and that the robust beam relay of the McColl pattern with plungers $\frac{3}{4}$ in. or even 1 in. square be used, then the scheme possesses the following characteristics: The relay is more than strong enough to resist any possible force that can be imposed upon it in practice, the energy supplied by the transformer is amply sufficient to operate it, and the protection given is of a high degree of sensitiveness. To quote a specific instance of the last feature, a dead-ended feeder when protected by an unbiased system on the usual opposed-voltage principle may in practice require a leak to operate it equal to 250 per cent of the normal full-load current. Using the biased system just specified, reliable operation will be given for faults equal to only 5 per cent of the normal full-load current, and the limit has not yet been reached in the downward direction. These particulars will, I think, compare very favourably with the similar particulars given in the paper. I have mentioned the McColl system, first because so far as I know it is the only one in use, apart from Mr. Wedmore's parallel-feeder scheme, which employs a biased relay, and secondly because several figures in the paper are simply the McColl figures with the biased transformer inserted in place of the relay. For example, Fig. 2 is equivalent to Fig. 16 in Mr. McColl's paper,* with the two windings in the current-transformer circuit removed from the relay and placed upon a transformer which has a secondary winding actuating a separate relay. In connection with this similarity a further point should be mentioned. The author has rightly enforced the necessity for the utmost simplicity and robustness in connection with the design of protective gear. Yet comparing these two diagrams it is seen that, first, the author has added to the simpler one a complication in the shape of the biasing transformer, and secondly, he still uses a delicate form of relay. The design of the latter is shown in Figs. 15 and 16, and I consider that it is too finely proportioned and moves through too small a distance to be classed as a robust article. With regard to the addition of the biasing transformer, Fig. 11 shows two of these added to a single scheme, while Fig. 13 actually shows three additional transformers, which would presumably make five transformers in all, counting the one at either end of the apparatus to be protected. Surely the author cannot maintain that these additions bear out his ideal of simplicity. He has evidently great faith in the reliability of transformers; it should nevertheless be remembered that these involve the addition not only of numerous windings but also of separate leads and joints, and all of these constitute additional members of the installation which introduce further possibilities of failure. It has been my experience that the current transformers of a protective system

* "Automatic Protective Devices for Alternating-Current Systems," *Journal I.E.E.*, 1920, vol. 58, p. 525.

are the most likely portions to give trouble, the number of cases in which I have found the connections of units made by different firms to be wrongly marked being quite out of proportion to defects in the rest of the apparatus. The author proposes on page 577 to employ a transformer to do the work of an auxiliary switch. He further suggests on page 579 that an auxiliary d.c. switch and a transformer should be employed instead of the three a.c. auxiliary switch contacts in order to render the apparatus less sensitive to the initial rushes of current that are experienced when switching a power transformer into circuit. Now the difficulty attending the solution of this problem is to prolong the short-circuiting of the protective gear for the few periods after the transformer is switched in during which a high transient current lasts. The movement of the oil switch from the closing of the arc-tips to the final position of the contact is in the vicinity of 3 in., and allowing ¼ in. break for the auxiliary switches, and a closing speed of 5 ft. per second for the main contacts, the time taken by the switch to travel this short distance is at most 0·04 second, which represents only one period for a 25-period current. Thus, it is practically impossible to avoid by a simple switching arrangement the effects of this transient switching current, as a short-circuit of only about one-period duration is not sufficient to exclude it from the protective gear. It is necessary with the ordinary a.c. pattern of auxiliary switch to employ some species of time-lag to keep the protective gear out of action a few periods longer. It would not appear that this difficulty is solved by the d.c. switch and transformer arrangement proposed by the author. Dealing with the reliability of auxiliary switches, it is my opinion that these are at least as reliable as the main switches. Consequently I am in favour of using them in preference to transformers. I do not quite follow the author's arguments in favour of a statical method for obtaining the bias. The great aim in designing protective gear, as with other forms of electrical equipment, is to obviate moving parts as far as possible, since they are always points of weakness. Now it is impossible to do without a moving element altogether, since a relay is an essential part of the scheme. If, then, the number of moving parts is restricted to one, and the number of leads, contacts and statical portions generally is reduced to the smallest limits, the maximum of reliability will be obtained, quite irrespective of the functions of the different parts of the apparatus. For example, a relay is no more unreliable because its fulcrum has been moved a slight distance from the central position, thereby endowing it with a bias. I can appreciate the author's wish to employ a single form of relay for every species of protection, but this is by no means confined to the system that he has described. The McColl systems employ exactly the same pattern of beam relay for feeder, generator, transformer and parallel-feeder protection, the windings and the position of the fulcrum only being modified to suit the particular cases. A further scheme with special characteristics, in which an induction directional relay is used, is provided as an alternative for generator protection, and the same type of relay is preferable for the distant end of parallel feeders since it gives somewhat more complete protection than the beam pattern. In connection with the operation curves shown on page 565, it would seem that the most sensitive operation is given at no load. There is a wattless current passing into the apparatus and not passing out of it at this value; it thus functions as a leak and would trip the relay if the latter operated at less than about 5 per cent of normal full load at this point. With the beam relay it is possible to raise this end of the characteristic curve by the adjustment of the counterweight, without increasing proportionally the settings at other points, an advantage that would appear to be wanting with other forms of relay. The author's scheme shown in Fig. 32 for split-conductor protection seems to me to be immune from the criticisms I have made as to complexity, since it possesses one transformer only which is connected by a single circuit to the relay. This system appears to be excellent, and I was somewhat disappointed to find that the author preferred the scheme shown in Fig. 34. I should be glad to know the reason for this preference.

Mr. A. E. Angold: The scheme for using the B/H characteristic of iron as a "valve," which has been so ingeniously embodied in the biasing transformer described by the author, deserves a fuller description. A somewhat similar application, viz. to magnetic shunts for exciter dynamos, was described by Stoney and Law in a paper* read before the Institution in 1908, and one would have expected the principle to be used for a variety of purposes, but probably the losses in the iron due to high densities and a.c. excitation are against it. In this instance the author may be paying too dearly for his static bias. How much larger does he need to make his current transformer in order to provide the extra magnetizing current, or to what degree has he been obliged to reduce the power in his relays as an alternative? The advantages of his scheme are: (1) A static bias instead of a mechanical bias, and (2) one coil on the relay instead of two. The disadvantages are: (1) An extra transformer, and (2) larger current transformers or, alternatively, a weaker relay. The author suggests the use of relays taking "a few volt-amperes" and speaks of a relay operated with 0·5 volt-ampere—presumably that is the amount required to overcome the controlling force. Such relays must necessarily be flimsy instruments and therefore will offset any advantages gained from the employment of static bias. With single-element relays taking 0·5 volt-ampere at 50 periods, the total work done would be about 0·02 ounce-inch, that is to say, an armature moving 0·1 inch would have an initial pull of 0·2 oz. with 0·5 volt-ampere. Disc motor relays of the shaded-pole type would do about the same amount of work with a 45° movement of the disc. This is all used for balancing the mechanical controlling force and, if the relays are to make contact with not more than 10 per cent increase, the energy available for contact pressure would be only one-fifth of these figures for the disc relay, and one-third to one-half for a magnet relay, assuming the armature of the latter to be practically touching the poles at the conclusion of the operation. The author states that it is usual to employ more or less complicated means of augmenting the contact pressure, and the above

* *Journal I.E.E.*, 1908, vol. 41, p. 286.

figures show how necessary it is to do so. It would appear that the more practical way is to put in larger, stronger and more efficient relays, providing this can be done without making the current transformers too large.

Dr. C. C. Garrard: In discussing the paper I should like first to put in a plea for simplicity. Protective gear is rather complicated, but it must be remembered that as it has to be operated by switchboard attendants who are generally not highly technical, the success of the gear depends upon its being easily comprehended by these men. There is no doubt that the principle of the bias applied to protective gear is correct. The older systems of balanced protective gear did not have this bias principle, consequently their action left much to be desired. It must be remembered that these unbiased protective systems are no longer installed, except in those cases where the purchaser is not familiar with the advantages obtainable with the biased systems. The author has compared his system, in a number of instances, with old-fashioned unbiased gear, but it would have been better if the comparison had been made with more up-to-date systems. The bias may be given to the protective gear in various manners, mechanically, electrically or magnetically. The author introduces a special biasing transformer to secure this end; this is a very ingenious method and will doubtless give excellent results, but I strongly disagree with him in his statement that the resulting system scores on the grounds of simplicity. In any case it is an additional piece of apparatus. If we consider the biasing transformer shown in Fig. 22, for example, so far as I can see this has some 30 terminals, and to secure a correct action they must be connected up in a definite order. The number of possible permutations and combinations which can be obtained with 30 terminals is very large, and I contend that Fig. 22 is very much more complicated than the system in which the bias is obtained mechanically in the relay. The author also raised the point that a static apparatus, such as the biasing transformer, is not as liable to alter in its calibration as is, for example, a relay. I do not quite see the point of this argument, as in any case the author's system embodies a relay with its inherent possible faults. Moreover, a transformer, especially if it has an air-gap, has been shown by experience to be liable to alteration in calibration, due to short-circuits. Further, the author lays stress on the fact that he employs only one kind of relay, and claims great uniformity. It would appear, however, that his system requires various types of biasing transformers for the various schemes of protection. From this point of view, therefore, it seems to me that there is not much in the author's contention. Further, as regards generator protection, it is very often deemed essential to protect generators not only against faults to the frame but against reversals, or, what is very much more important, against incipient faults due to short-circuited turns before these have time to burn through the slot insulation and cause a fault to the frame. A special relay which will give this additional protection is, under these circumstances, justified.

Mr. A. S. FitzGerald (*in reply*): The author's thanks are due to the various contributors to the discussion, and particularly to the supply engineers whose experience of the operation of protective gear forms a useful addition to the available information on the subject.

General.—Having regard to the remarks of several speakers it would seem desirable to emphasize the object of the paper, which is, however, exactly that indicated by the title. It is intended to deal with the design of apparatus for all the differential protective systems which have been used in this country, to a sufficient extent to justify their notice in a paper of this form, rather than to discuss at length their relative advantages and disadvantages. It should be no argument against the particular method of designing balanced-power gear described in the paper that this system of protection is not so good as, for instance, a pilot-wire system. Whilst it is realized that no engineer would install balanced-power equipment if it were possible for him to use a pilot-wire system, there are, without doubt, occasions when circumstances justify or (as mentioned by Mr. Trencham) necessitate the installation of the less perfect equipment. Thus the fact that such systems have been installed in a number of cases leads to their being dealt with in the paper. In the same way, the remarks of some speakers in respect of fault settings, although interesting and an undoubted addition to the discussion, do not seem to be relevant criticisms of the methods advocated in the paper. If there were no demand for sensitive fault settings, the design of protective gear would unquestionably be greatly simplified. The principal object of the paper is to show how apparatus can be built which will give low fault settings and be at the same time perfectly stable. It is realized that the apparatus is not necessarily applicable if heavy fault settings are not objected to.

Captain Donaldson has referred to the considerations governing the selection of protective gear and has pointed out that it is not always justifiable to legislate at considerable expense for conditions which seldom arise. The provision of protective gear is a form of insurance and the amount of money expended depends entirely on the justifiable risk. Sometimes it is necessary to cover every possible chance and to put in comprehensive and extensive protective gear. In other instances it is not necessary to do so; yet where equipments of the latter category are installed, it is often remarked that the apparatus is unsound because it only covers the definite conditions envisaged and not every conceivable and less probable class of fault.

By far the most striking feature of the discussion has been the conflict of opinion on general principles of design between the users of protective gear on the one hand and manufacturers on the other. Many of the former complain bitterly of the unsatisfactory performance of protective gear and adopt the general attitude that protective gear is a necessary evil and that the less of it they are compelled to install, the better for all concerned. In contrast to this attitude, the principal comment of manufacturers is that modern

protective gear is so nearly perfect that the author's efforts towards improvement are unnecessary and superfluous. The individual, therefore, must judge for himself as to which of the above standpoints most nearly represents the true facts of the case.

The apparent complication of some of the biasing transformer circuits has been mentioned. In many systems of protection the operating conditions and the problems met with are singularly complex, and absolute simplicity can only be achieved by arrangements which do not cover every requirement, or which are unable to perform with complete satisfaction under severe operating conditions. In the field of protective gear it is usually the case that the more one is prepared to expend, the more simple is the system that may be installed, and in cases where the choice of protective gear is influenced by the desire to spend a minimum amount of money on the same, some degree of complication is a necessary penalty which must be paid.

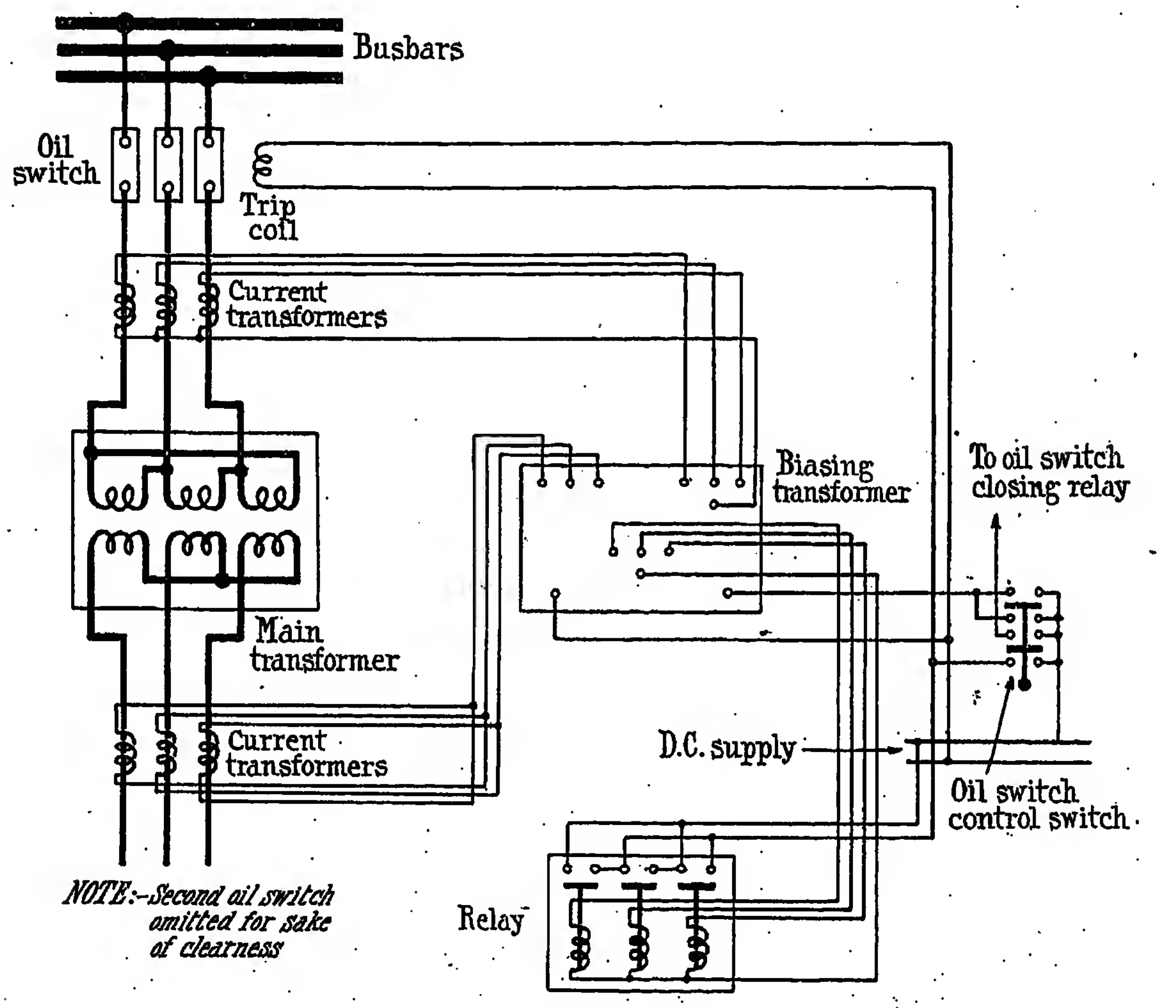

FIG. J.

In the discussion there is inclined to be some confusion between complication in the description and explanation of the circuits, and complication in the actual reality. Dr. Garrard's criticism of Fig. 22 typifies this attitude of mind. Fig. J, which gives the practical wiring diagram corresponding to Fig. 22, shows that Dr. Garrard's animadversions on the subject of 30 terminals are not quite to the point. A study of the various wiring diagrams given in the paper will show that close attention has been given to the grouping of the terminals on the biasing transformers with a view to facilitating correct connection. It can scarcely be contended, for instance, that there is any reasonable possibility of error in making connections in accordance with Fig. J, even though highly skilled erectors be not available.

The author has definitely been at pains, particularly in systems of an inherently less simple nature, to arrange that such complication as may be unavoidable shall reside in the design and manufacture rather than in the installation and maintenance of the protective gear. Mr. Howarth has criticized this policy and it is of course realized that in this respect differences of opinion are bound to exist. Some engineers may prefer to acquire and erect, connect and adjust protective systems and relays, providing a staff competent to understand thoroughly and maintain the operation under all conditions. On the other hand, the author feels that the majority of engineers will find more convenient a form of protective apparatus specially designed to relieve them to a large extent of this responsibility and in which the apparatus is provided in a form requiring the minimum of maintenance and attention.

Stability.—By far the greatest volume of adverse criticism encountered during the discussion has been concerned, not with any particular arrangement devised by the author, but with the fundamental principle of design by means of which stability is to be obtained. Supply engineers have in unmistakable terms voiced their dislike of protective gear in general. It will hardly be disputed that the unenviable reputation gained by protective gear in the past is more associated with instability than with any other shortcoming. It is therefore surprising to find so many speakers who are still prepared to attack the principle of the biased protective system as such and to express their decided

preference for methods requiring accurate balancing of protective transformers.

The author, as mentioned in the paper, has felt justified in assuming agreement with the biasing principle, but it would appear that its advantages are still not appreciated in many quarters. Thus it seems desirable to describe more fully the grounds on which the biasing principle is felt to be the most satisfactory method of ensuring stability. The history of protective systems, as indicated by personal experience and published information, records continual failure to achieve stability. That this would not have been the case had biased systems been more generally employed is supported by the operating experience with such systems. It is, however, now asserted that, as a result of experience, balancing troubles have been entirely overcome. The author has referred to the very great responsibility assumed by a protective system, and several speakers have emphasized this point. It is therefore maintained most emphatically that such responsibility warrants a much greater margin of safety than is ever obtained by balancing methods.

As mentioned by many speakers in the discussion, it is no doubt possible to get current transformers which on a "through current" test of a certain magnitude will not trip the relay. By how much, however, is the out-of-balance current under these conditions less than the tripping current of the relay, and to what extent will the balance be maintained with greater currents? What will be the effect of any possible change in the magnetic circuit over extended periods due to possible ageing of the iron or the effect on the transformers of handling after testing and erecting? It is known that manufacturers of magnetic steel are very careful as to the way in which they handle this material. Balance can never be checked after erection except as the actual result of faults. It is probably not realized, except by those who have actually carried out balancing tests, how extremely minute is the physical change in an iron core, representing the difference between perfect balance and tripping of a sensitive relay, when the core is excited by currents of the order of 10 000 amperes. Minute movements with air-gap cores, or slight changes in closed iron-ring cores due to temperature or varying eddy currents, have a very perceptible influence on the out-of-balance current under such conditions, and manufacturers of protective gear depending for stability on simple balance will seldom accept responsibility for its operation except within definite limits of current. Small differences in the protective secondary circuits due to lack of symmetry of resistance and reactance may set up similar small out-of-balance currents, and the possibility of cumulative circuit and transformer differences renders the whole process somewhat hazardous.

Many instances of perfectly successful experience with such equipments can be cited, but so also can cases of failure to secure stability, many speakers having referred to such instances. Only where a biased system is adopted can the element of chance be avoided. When a biased system is carried out on the lines described by the author, there is no doubt whatever as to its ability to withstand "through" short-circuit currents. There is an ample margin for any contingency, and the more severe the fault the more certain is the stability. The out-of-balance current necessary to trip a properly stabilized biased system when traversed by a current of short-circuit value is very large indeed in proportion to the maximum divergence encountered with ordinary current transformers.

The author's contention is even supported in a measure by one of the speakers in favour of balancing methods. Mr. Biles, after referring to the absence of difficulty in the balancing of transformers, describes a scheme of generator protection devised by him in which he finds it necessary, in order to ensure stability with low fault settings, to employ a diverter relay arrangement. This entails extra resistances and double the normal complement of contacts and moving parts; unless these are specially timed the arrangement will not work. It is frankly an alternative to a biased system, and one which in the opinion of the author accomplishes its object in a much less perfect manner than does the biasing transformer. It is difficult to understand how the extra complication may be justified unless some difficulty in properly balancing the transformers does in fact exist.

Biased relays.—Mr. Cheetham agrees with the remarks in the paper in respect of the advantages of simple relays over the more complicated biased relay. Mr. Wilson, however, prefers the biased relay. The great risk inherent in all balanced-beam relays is the possibility of sudden kicks (such as might be due to momentary overloads) operating in a restraining direction, causing a rebound on to the contact, and this difficulty is not always envisaged in attempting to design such relays.

Design of biasing transformer.—Mr. Clothier, in comparing the action of Mr. Biles's diverter relay system with the operation of the biasing transformer, makes a statement indicating that with a biasing transformer the restraint is always present. This is not in accordance with the facts indicated by Fig. 5 and the accompanying description.

Mr. Lipman inquires as to the consumption in volt-amperes required to operate the restraining windings, and particularly how the biasing transformer may be applied to extra-high-tension installations where, due to the restricted output of bushing and other forms of current transformer, little energy is available in the protective circuit. The amount of power used in a restraining winding in order to prevent operation of the relay varies between an amount equal to the operating volt-amperes and double this figure. The arrangements described in the paper are already being built for 110-kV systems. In these instances it has been found that the bushing transformer output is comparable with that obtainable at the usual voltages employed in this country. Where, however, it is desired to employ the whole of the bushing transformer output for operating, the arrangement of restraining windings shown in Fig. 1 (*a*) and applied in Fig. 34 is particularly suitable, the restraining energy being derived directly from the primary.

Mr. Howarth refers to the method of making a mid-point tapping on a dividing restraining winding. It may be pointed out that where this form is indicated by the symbol shown in Fig. 2, the horizontal winding should be taken as representing a pair of divided restraining

coils; thus two pairs of coils will be provided and connected in series when a mid-point is desired.

Mr. Ross questions the statement in the paper as to the absence of any difficulty as regards the internal balance of the biasing transformer. The facts are, however, exactly as stated in the paper. These may be more fully comprehended if it be recalled that the cross-section of the core of a biasing transformer is of the order of 1/30th of the cross-section of a typical current transformer. Suppose, therefore, that owing to some variation in the iron there is 1 per cent difference in permeability between the two halves of a biasing transformer or between one ring and the other. This will cause a 1 per cent difference in the total flux. The energy developed in the relay as a result of this difference will be a constant multiplied by the difference in flux; thus this difference will be much greater in the case of current transformers than in the case of the small biasing-transformer core, where in fact it is not found possible to detect such differences. In the rectangular type of core, in any case, any difference in the laminations is likely to be balanced between the two sides by the ordinary methods of assembly.

Mr. Angold also refers to the question of the energy necessary to provide the static restraint, the figures being mentioned above. The extra output from current transformers necessary to overcome the loss in efficiency where the biasing transformer is operating as a straight transformer is not serious. The figures are given on page 573. Moreover, so far as overload restraint is concerned—and this is by far the greater field for the biasing transformer—the greater energy is only desired under heavy current conditions when ample magnetizing current is readily available.

Mr. Cheetham inquires as to the meaning of the fifth paragraph dealing with the advantages of the use of a biasing transformer. This particular point refers to the matter discussed in col. 2 on page 565, describing how the saturating effect of the biasing transformer, even when not restrained, limits the maximum current that can be reached in the relay winding. Mr. Cheetham will find in Fig. 22 a practical example of the method of d.c. control suggested on page 573. Fig. 9 is intended only for explanatory purposes, and the limitations mentioned by Mr. Lipman are referred to in the paper. The complete connections of such a system are given in Section 2 of the paper, several diagrams being shown. Fig. 36, for instance, does exactly what Mr. Lipman suggests.

Dr. Garrard rather surprisingly questions the permanence and robustness of the biasing transformer itself. He suggests, for instance, that the air-gap in the biasing transformer may, by alteration, affect the performance of the apparatus. In the first place, a reference to Fig. 5 will show that any small change in the air-gap will have very little effect on the protective gear, as the particular value of overload at which the bias begins to become effective is not a matter of very great importance. Critics of novel apparatus are also sometimes rather liable to mention small points of this nature with a view to questioning the satisfactory operation of the gear, without giving the designer reasonable credit for carrying out his design in a practical manner. Thus although, as indicated, the accurate dimension of the air-gap is not in certain biasing transformers a matter of great importance, in all biasing transformers designed by the author the laminations are pressed hard home on an insulating filler carefully cut to the exact dimensions required. Moreover, the biasing transformer is on completion made solid with compound. It is only by careful attention to such details that satisfactory operation of protective gear can be obtained, and it is possible that a part of the lack of success of protective gear in the past may be attributable to some of the more subtle points not having been given adequate attention. It would seem, therefore, that Dr. Garrard's criticism in this respect is not admissible. He also refers to the question of the use of one type of relay throughout all the different systems of protection, in contrast with the more usual method of designing special relays for each system.

It is suggested by Dr. Garrard that inasmuch as a different design of biasing transformer is necessary, the standardized relay offers no advantages. He will realize, however, that this is not the case if he will consider practical methods of manufacture of an apparatus such as the biasing transformer, which lends itself particularly to standardization of components and tools. Thus a single core of a biasing transformer will be built of identical components in whatever system of protection it appears, and the only variation between one biasing transformer and another will be in the windings and connections.

Protective transformers.—There would seem to be little disagreement with the author's plea on behalf of bar-primary protective transformers. On the other hand, a number of contributors to the discussion favour the air-gap transformer in lieu of the ring-core type recommended by the author. Having regard to the frequent comments heard in the discussion as to the flimsiness of some of the protective relays extant, it is surprising that so little exception is taken to the inherent limitations of the air-gap transformer. The author recently had occasion to test a typical air-gap transformer in comparison with one of his opposed-voltage transformers of comparable rating. For given primary current the output of the latter in volt-amperes was exactly 150 times that of the former. The mere fact that the use of the ring core enables a very much more robust relay to be employed is, in the opinion of the author, the strongest possible recommendation for its use, anything tending to eliminate the necessity for flimsy relays being, it is felt, a step in the right direction.

Relays.—Arising out of the above remarks, it is noteworthy how much difference of opinion exists amongst engineers as to what really constitutes a robust relay. As indicated in reference to the question of protective transformer design, the author feels that the greater the operating forces set up in any relay, and the more robust the relay, the better is the protective system, other considerations being equal. Several speakers, having in mind standard Merz-Price feeder protection, describe as robust a relay that will give with that system of protection a fault setting of several hundred amperes. This relay would trip at something not very much exceeding 0·5 volt-ampere. It is a relay of this

order of sensitivity that has largely been used by the author for operation with the various biasing transformers, and there is no difficulty in making such a relay quite immune from the heaviest mechanical vibration. That this class of relay has not in the past been free from this trouble is referred to by Captain Donaldson.

Mr. Angold, on the other hand, who is evidently concerned with a much heavier class of electrical apparatus, is inclined to regard such a relay as undesirably sensitive. There are on the market, however, relays such as the Fawssett-Parry mentioned by Mr. Buist and that described by Mr. Cheetham, capable of very much finer settings than the 0·5 volt-ampere relay, and, whilst in the opinion of the author these are much too delicate, a certain amount of success has no doubt been achieved by them.

Mr. Wilson criticizes the practical design of Figs. 15 and 16. These figures are, however, intended more as diagrammatic representatives of the principles involved than as an attempt at a practical design. Mr. Wilson suggests that the balanced-beam relay is preferable to the attracted-armature relay, on the grounds that it moves through a greater distance. A probable result of this is that the operating forces are smaller. It is the small air-gap in the attracted-armature relay that gives rise to the large forces set up by this class of relay. A properly designed armature relay, having light moving parts restrained by springs, will unquestionably be less affected by mechanical disturbances than the balanced-beam arrangement having considerable moment of inertia about its fulcrum.

Mr. Lipman disagrees with the proposal to employ similar relays for all purposes, suggesting that it is better to have a distinct type of relay for each different function so that different classes of abnormality may be identified. This may be pleasing but is unquestionably an uneconomical proposition, and in any case it would seem that Mr. Lipman's preference could surely be met by the use of distinctive name-plates.

Reference is made in the discussion to the development taking place at the present time in respect of dispensing with the relay altogether and utilizing a modification of the protective relay, adapted directly to trip the switch. Much may be said for and against this practice. The advantages are that it cuts out a definite link in the chain of events between the occurrence of a fault and its isolation, and as such should provide greater reliability. On the other hand, particularly where sensitive settings are required, it still suffers from the inherent restrictions mentioned in the paper, notably in respect of the limited power available. The electromagnetic element therefore is bound to be a light affair in comparison with the usual switch mechanism, whether it works contacts or releases a series of mechanical latches. As such it will require proper attention if it is to give satisfactory operation. If it is a relay it will be found on the front of a panel properly protected by means of a cover, having probably a glazed front, and will be under constant observation. If, on the other hand, it is built in the form of a light tripping device, it will be buried away somewhere in the switch mechanism and may probably be situated in a part of the power house where the atmospheric and other conditions are less favourable than is the case in the position where the switchboard is installed. Moreover, it is impossible to adapt a sensitive form of tripping device to operate directly the oil-switch tripping mechanism. There has to be some form of link connecting the electromagnetic element with the standard tripping mechanism of the switch. This takes the form of a mechanical arrangement controlled by very small forces, and, unless very special care is taken in this design, it is unlikely to prove any more reliable than the conventional methods of using a relay and trip circuit. The author is of the opinion that any attempt to provide a light tripping device comprising an adaptation of existing forms of sensitive relay will not give satisfaction, for the reasons mentioned above. If, on the other hand, it should be found possible to devise a sensitive relay in a more robust form, and such that it may directly operate the switch mechanism without any mechanical amplifying device, then it should be very desirable and reliable.

Phantom auxiliary switch.—Mr. Clegg asks what would happen in the circuit shown in Fig. 20 if the d.c. supply should fail. Consideration of the diagram will indicate that the most conspicuous result would be the impossibility of opening the oil switch if the tripping supply is not available. The effect on the protective circuit of failure of the d.c. supply would simply be identical with that of failure of an ordinary auxiliary switch to close, i.e. that the normal circulation of current would be impeded by the reactance of the current-transformer secondary windings, and that the protective relays might be operated by "through" overloads, it being assumed that the oil breaker on the feeder concerned is open and that the neighbouring feeders are carrying load.

Generator protection.—Mr. Cheetham refers to the method of protecting a generator on the circulating-current system with an earth relay in the neutral lead. This is quite a desirable arrangement, and the principle of separating earth faults from other faults is fully exploited in the paper. It should not be forgotten, however, that a divergence between the magnetic characteristics of one transformer and its two neighbours will set up out-of-balance currents even in leakage relays, unless the balance is perfect or the device properly stabilized by employing a suitable biasing feature. It will be noted from the paper that all leakage relays operated by three current transformers are provided with overload restraint, on the occurrence of heavy "through" faults, to take care of this.

Several speakers refer to the protection of generators by reverse-power apparatus against failure of the field. The scope of the paper, it will be recalled, is defined as covering only differential systems of protection, under which reverse power protection may hardly be classed. Moreover, the failure of the excitation is not such a serious emergency as a fault in the machine windings.

General dislike of potential-operated protective gear has been evinced during the discussion, and it is open to question whether such methods of protecting generators are really worth while. It is the standard practice in automatic stations to protect all large machines with a low-field-current relay, and this would seem to be a suitable and simple method of accomplishing this object.

Transformer protection.—Mr. Howarth refers to the desirability of low fault-settings, where a transformer is protected by circulating-current balance between primary and secondary windings in order to give adequate protection on the occurrence of faults between turns on a single winding. It is doubtful whether any great degree of effective protection can be given from faults between turns, except in the more improbable case of their embracing a large proportion of the total winding. Mr. Ratcliff, for instance, recommends the separate protection of the primary and secondary windings of a transformer. By so doing, he avoids any difficulty due to the magnetizing current, yet at the same time with such an arrangement no protection is given from faults between turns.

Mr. Howarth also makes a pertinent inquiry in respect the paper, the author is of the opinion that every contact saved is a step in the direction of reliability.

Reference has also been made to the possibility of reducing the amplitude of the magnetizing-current transient by charging resistances. There is much difference of opinion, however, as to the desirability of this device from the point of view of reliability and safety of the oil switch, and the author feels that there is a distinct field for the device described.

Mr. Wilson refers to the question of the effectiveness of the arrangement from the point of view of duration of the disturbance. In general, the larger the transformer the greater is the duration of the magnetizing-current disturbance. In the case of plant of large capacity, one would expect in almost every case electrically-operated oil circuit-breakers, in which case the

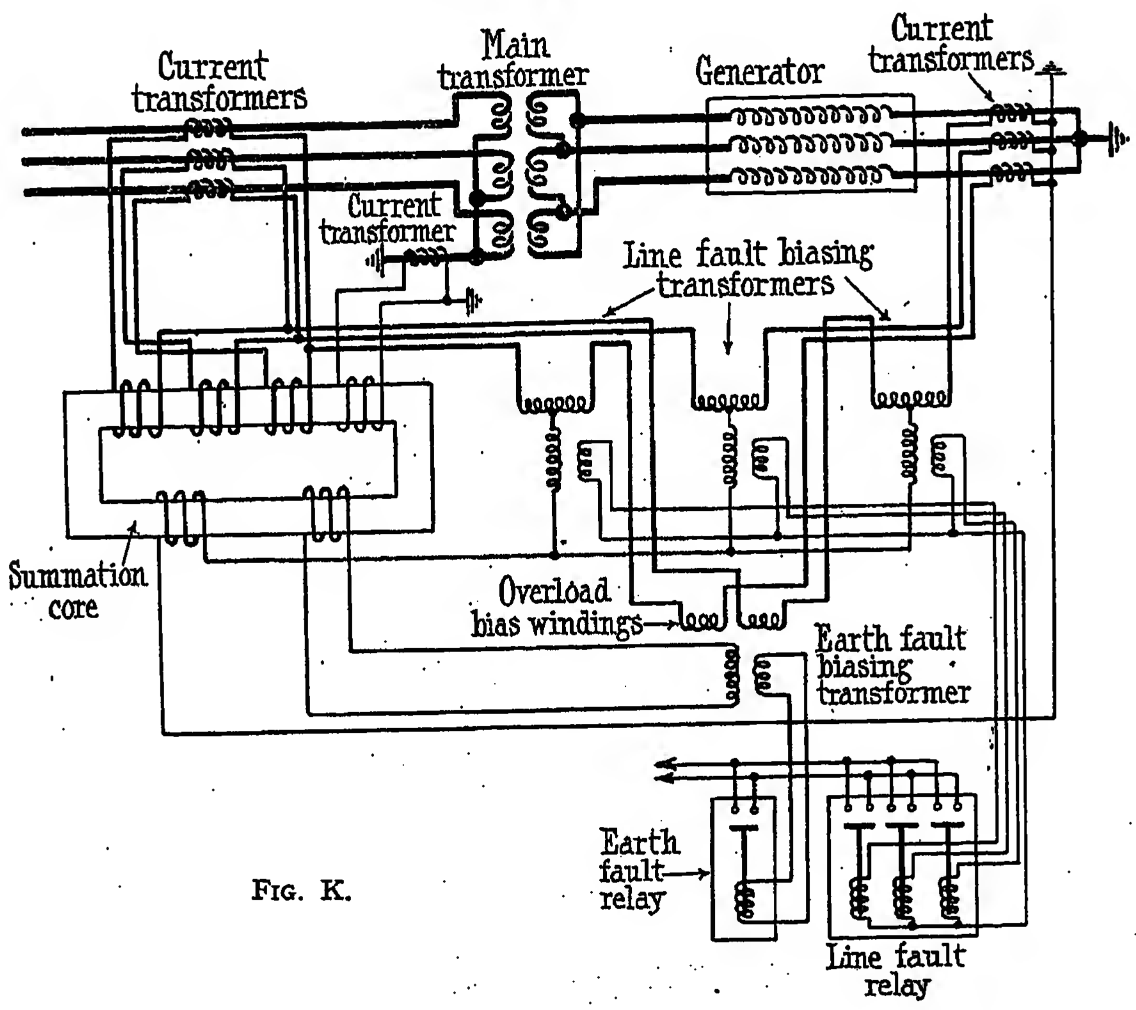

FIG. K.

of the growth of the direct current which is employed in the circuit shown in Fig. 22, to prevent operation of the relays due to the magnetizing-current transient on switching on. Owing to the entirely unknown extent of this trouble in different installations, it is usual to supply a resistance having a number of tappings for connection in series with the d.c. restraining winding. The object of this is two-fold: first, to ensure that the direct current shall grow instantly to its full value, the importance of which is pointed out by Mr. Howarth, and secondly, to enable the extent of the d.c. bias to be suitably adjusted in accordance with the magnetizing characteristics of the transformer protected. Mr. Cheetham refers to a similar scheme by means of which fuses are automatically connected in parallel with the relay windings while the transformer is being switched in. This leads to a triple-pole auxiliary switch, however, and, as stated in connections shown in Fig. 22 would be employed. With this arrangement, the control switch may be held on as long as desired, the full sensitivity of the protective circuit only being restored when the control switch is released. It is generally only the first two or three periods of the magnetizing-current transient which are of serious amplitude, and, where hand-operated oil switches with special auxiliary switches are employed —this arrangement being more commonly found on the smaller transformers—the d.c. circuit remains energized for a sufficiently long time to avoid tripping of the relays, even if the magnetizing current has not quite reached its steady value.

Combined protection of generators and transformers.—Mr. Ratcliff and Mr. Marshall have referred to the inherent difficulties of undertaking the combined protection of generators and transformers on the circulating-

current system. These are associated with the fact that in the event of the alternator suddenly losing its load it is impossible to prevent a transient rise in pressure. With modern highly saturated transformers, such a rise may cause an enormous increase in the magnetizing current. So far as the circulating current is concerned, this is definitely a difference current and corresponds to a fault. In the case of the Manchester Corporation generators, an increase of 20 per cent in the pressure resulted in a tenfold increase in the magnetizing current. The difficulties of protecting such an arrangement are therefore obvious.

Figs. K and L show respectively the schematic and practical diagrams of a suitable circuit for protecting a combination of star-delta transformer and generator. Owing to the magnetizing current difficulty it will hardly be possible, without complicated arrangements magnetizing currents. In order to avoid additional sets of current transformers, a summation transformer is employed in order to arrange discriminating protection in respect of earth faults fed through the current transformers which are connected in delta. In other respects, the diagram is, no doubt, self-explanatory. The summation transformer is incorporated in the biasing transformer itself, and the practical diagram is as simple as can reasonably be expected, having regard to the scope of the protective circuit.

Opposed-voltage system.—The opposed-voltage protective system described in the paper has been adversely criticized by several speakers, who show a marked preference for the air-gap type of transformer, and it has been suggested that the combination of ring-core transformers and biasing transformers has no advantages over the elementary circuit with air-gap transformers.

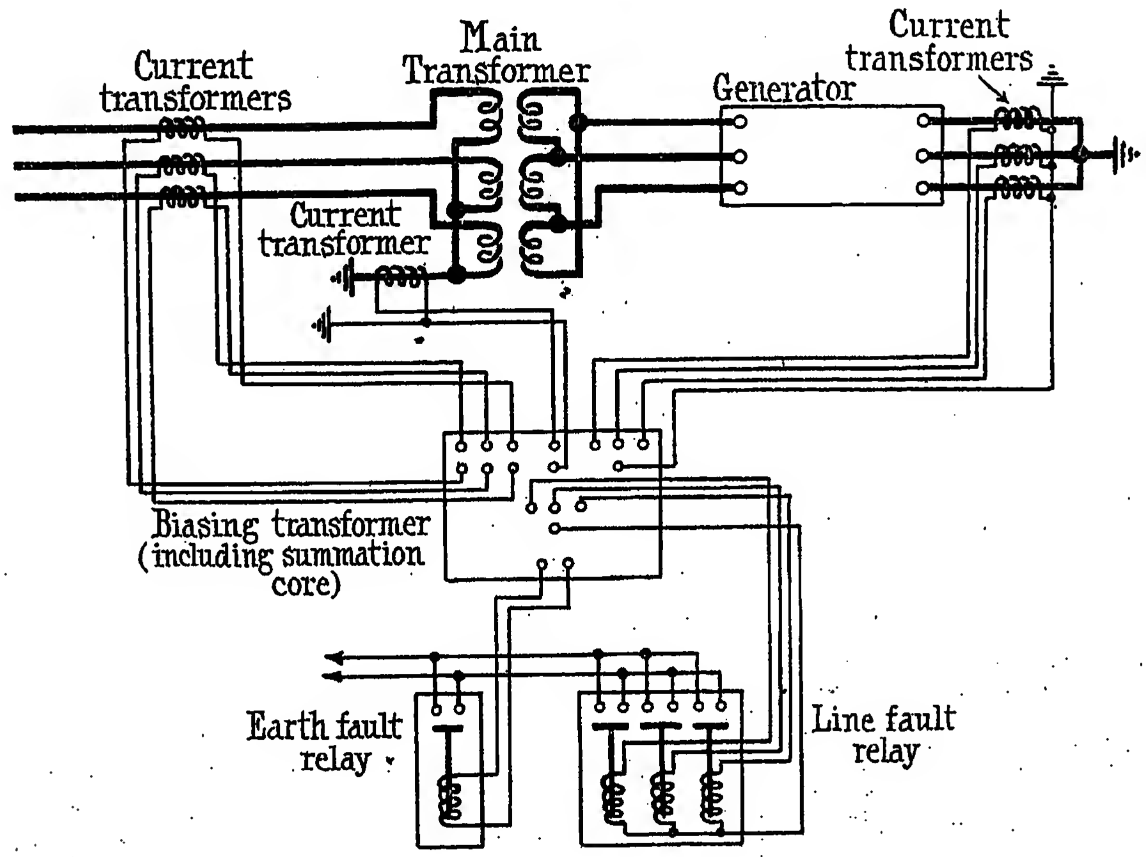

FIG. L.

involving potential, to maintain sensitive fault-settings on any circuit in which the magnetizing current difference is likely to appear. In the present arrangement, therefore, one triple-pole relay is provided which either will have fault settings sufficiently high to be clear of any magnetizing current disturbance or, as an alternative, may be provided with a suitable time-lag. This relay will be operative on the occurrence of faults between phases on the generator, transformer primary, or transformer secondary, windings. A further single-pole relay is provided which, as may be seen from the connections, will be tripped only by an earth fault on the generator or transformer windings. Neither of the relays will be directly affected by line or earth faults which may be fed by the plant protected. Both are provided with overload restraint in order to ensure immunity from operation, due to current transformer divergence. The earth-fault relay is not disturbed by The question of transformer design has already been gone into, but the author would emphasize that the whole point of using the biasing transformer and solid-core transformer resides in the fact that with such an arrangement (after making allowance for energy lost in the restraining windings) for any given primary earth-fault current the opposed-voltage system described in the paper will deliver into the pilot-wire circuit rather more than 50 times the volt-ampere output which can be given by the multi-gap type of transformer. These are actual test results, utilizing in each case transformers of similar rating. Inasmuch as for equivalent performance a heavier relay may be used in the one instance than in the other, it is maintained that this advantage alone more than outweighs any of the aspects of the arrangement which have been criticized.

Several speakers have discussed the question of simultaneous earth faults and their effect on this class

of protective gear. This has been dealt with in the paper and it would seem desirable to make more clear the relation between these operating conditions and the design of the opposed-voltage system. The opposed-voltage system as described can be made immune from incorrect operation due to through earth faults not limited by the value of the earthing resistance, with fault settings well below 100 amperes. The main advantages accruing from the particular form of circuit employed, i.e. with separate earth-fault and line-fault relays, is that it enables ring-core transformers to be employed without these operating on open circuit. This fact alone enables much more sensitive settings for earth faults to be obtained with a less sensitive relay, apart altogether from the question of the possible fault-setting in respect of stability.

Several speakers have drawn attention to the additional difficulties which are experienced in applying a differential system of protection to e.h.t. cable systems, in that, as mentioned by Mr. Clothier, the charging currents met with are a direct exception to the principle on which differential protection has been based. There are various obvious methods of meeting the difficulty, but at the present time it is impossible to say exactly which practical solution will be found to combine effective operation with the desirable simplicity of apparatus.

Mr. Biles describes an application of his diverter relay system to an opposed-voltage protective circuit. The diverter relay principle has already been dealt with. Mr. Biles's scheme may be analysed as follows: He has devised a modification of the protective circuit described in Fig. 24, in which only a 2-core pilot cable is installed. The circuit is interesting and possesses certain advantages, though it is doubted whether it will be possible fully to exploit the saving of one of the pilot cores, as pilot cables are so often installed before the protective gear is finally decided upon. In utilizing the one relay energized separately by earth faults and line faults, there is not the advantage residing in the arrangement described in the paper and having separate relays, in that in the latter the settings for earth faults and line faults may be adjusted independently, and, moreover, a definite indication is given as to which class of fault has occurred. A study of Mr. Biles's scheme appears to indicate that there is a critical value of simultaneous earth fault and line fault which would set up E.M.F.'s in opposition and might not prove operative. This is a remote case, however, and Mr. Biles is no doubt justified in ignoring it. Mr. Biles points out that the complete scheme has the same number of relays as the author's proposed scheme, but if biasing transformers were used there would only need to be two relays instead of four in Mr. Biles's scheme. Whilst, therefore, there is no reason whatever to suggest that Mr. Biles's proposals will not prove effective, it does not seem reasonable to claim that any arrangement of diverter relays is as simple or likely to prove as reliable as the arrangements described by the author, where the additional functions are performed with static gear.

Mr. Ross discusses the practical design and operation of the opposed-voltage circuit described. The difficulties envisaged by Mr. Ross do not, however, occur in practice.

Split-conductor system.—The author's proposal to embody overload restraint in a split-conductor transformer has met with a good deal of opposition on the lines which have already been mentioned in the reply. Such speakers have most emphatically declared that the split-conductor system is absolutely faultless in operation, whereas other speakers who have referred to split-conductor gear have mentioned cases where it has been found to trip on "through" faults. It is therefore again the fundamental question of balanced versus biased systems. With balanced systems it is no doubt possible to get a very large degree of success, but there are quite sufficient cases of failure to have been mentioned several times in the discussion. Thus it is felt by the author that the employment of a definite stabilizing influence, whereby certainty of successful operation —so far as immunity from tripping on "through" overload is concerned—is ensured, is by no means uncalled for.

Parallel-feeder systems.—Much has been said in the discussion as to the disadvantages of parallel-feeder protective systems in comparison with pilot-wire systems. This point has already been dealt with.

A most surprising feature of the discussion is the number of speakers who have indicated their impression that parallel-feeder systems in general are of no practical importance. As Mr. Trencham rightly points out, this view seems to be associated with a certain amount of insular prejudice, such systems having been used to a large extent abroad.

The author recently communicated with one of the principal designers of protective gear in the United States in respect of the general status of parallel-feeder protective gear in that country. He was advised that parallel-feeder systems are regarded as a standard method of protection for large networks and that there is at present no sign of their losing popularity, the experience gained with them being very satisfactory. The author's informant indicated that definite records are available of over 1 000 installations and that the actual number of equipments was several times this figure; this being the case, it is no doubt obvious that the attitude of certain speakers is hardly tenable.

The general criticism is that parallel-feeder gear is likely to be disturbed by load currents. This difficulty was no doubt experienced during the initial development of some systems of this nature, but this particular point and its effect on design is gone into very fully in the paper. If this be adequately studied, it will be seen that the difficulties mentioned by the various speakers are explained and carefully avoided.

Mr. Leeson describes a semi-automatic scheme for the protection of parallel feeders. This, however, is not directly comparable with any of the schemes described in the paper in which the maintenance of continuity of supply is considered to be an essential feature. Mr. Leeson's arrangement, on the other hand, does not prevent a shut-down. Moreover, a close study of Fig. D shows that a potential transformer is indicated in an inconspicuous manner, although this is not mentioned in the text. If the potential transformer is existing there is, of course, no reason why it should not be used; but having regard to the remarks of Mr. Clothier

and other speakers on the subject of potential transformers, it seems very doubtful whether their installation purely for the object indicated in the figure is justified.

Separate treatment of earth faults and line faults.—Mr. Trencham emphasizes some of the practical advantages of this principle, and shows how the extension of the same to the design of switchgear itself might lead to enormous reduction in the required rupturing capacity of oil circuit-breakers, and thus in their cost. Lieut.-Col. Edgcumbe also supports this principle but prefers leakage arrangements involving direct or primary core-balancing instead of arranging leakage connections in the secondary circuit of the current transformers. It is, however, purely a question of circumstances, and in a large number of practical cases it proves to be a convenience to energize the protective apparatus from current transformers installed in accordance with conventional cellular arrangements. We have, then, systems of protection which may, without modification, be applied to a new system without deranging the existing connections. Moreover, the trifurcating box is included in the protected zone. Where a core-balancing transformer is designed to embrace all three phases, it will either be installed on the cable itself—in which case it will not include the trifurcating box in the protected zone—or it will be necessary to bring three insulated primaries through one transformer beyond the cable box, where to a large extent present practice favours phase separation.

Another advantage of separate earth-fault and line-fault settings is brought to light in dealing with Mr. Howarth's query as to the question of tee loads. Wherever it is desired to put a small tee load on any feeder protected by a system in which separate earth-fault and line-fault settings are employed, no modification need be made to the protective circuit nor need extra transformers be installed. The line-fault setting may be sufficiently high not to be affected by the difference current represented by the small consumer. The earth-fault setting will not be affected by any load drawn from the line in this manner. The arrangement will, of course, clear faults originating in the tee connection, but will not be affected by any condition of load if the respective lines are sound.

Fault settings.—Several speakers have inquired as to the fault settings that may be obtained with the apparatus described. Utilizing in every case a relay of any desired pattern capable of operating with 0·5 volt-ampere, the following performance is being obtained *:—

For generator protection, faults of 5 per cent may be cleared. This figure could also be obtained with transformer protection if the primary and secondary windings are separately protected.

For overall protection of a transformer, in which magnetizing-current differences are met with, it will probably prove desirable not to employ such small settings. This depends to a large extent, however, on the nature of the system on which the transformer is installed, as magnetizing-current transients other than those occurring during switching are largely determined by disturbances in the system pressure.

With split-conductor systems there will be no appreciable change in the fault settings now being obtained, if the overload restraining feature be incorporated.

In both the balanced-current and balanced-power systems for the protection of parallel feeders, the relay will be operated by earth faults which set up difference currents equal to 20 per cent of the feeder rating. For line faults, as has been mentioned, higher settings exceeding normal loads are desirable.

In the case of the opposed-voltage system—this being definitely the most successful of any of the systems described in the paper—a special design of current transformer has been made to enable the best possible fault settings to be obtained. For an 11 000-volt system this transformer is about 7 inches in diameter and about 7 inches long, and fault settings of the order of 50 amperes may be obtained on feeders of average length.

Costs.—Mr. Woodhouse inquires as to the cost of protective gear of the nature described in the paper. It will no doubt be appreciated that it is very difficult to give definite figures of cost for different classes of protective arrangements, owing to the diversity of conditions met with. It may be definitely stated, however, that in none of the schemes described in the paper is it found that the total cost exceeds that of corresponding unstabilized protective gear.

The cost of the biasing transformer is not heavy, owing to the manner in which it peculiarly lends itself to standardization. This cost is amply balanced by savings in other directions, such as the avoidance of the use of expensive and highly sensitive relays, elimination of the anti-capacity sheaths in pilot conductors, and the avoidance of the necessity of balancing transformers. Moreover, the arrangements described lend themselves more easily to economy as regards spares and replacements, owing to the fact that standard transformers may be drawn from stock without having to be specially made and balanced.

* In every case, except the opposed-voltage circuit, the figures given refer to the use of standard current transformers.

THE RISE AND DISTRIBUTION OF TEMPERATURE IN SMALL ELECTRICAL MACHINES.*

By EDWARD HUGHES, B.Sc.(Eng.), Associate Member.

(*Paper first received* 31*st October*, 1923, *and in final form* 11*th January*, 1924.)

SUMMARY.

The paper deals with the factors influencing the shape of the heating and cooling curves of coils and electrical machines. The thermal conductivity of the insulation is calculated by alternative methods from the distribution of temperature in coils; and the effects of different temperature-rises and of different air velocities upon the thermal conductivity and upon the temperature-rise per watt are considered. A new arrangement for measuring the mean temperature-rise of field windings is described. The temperature-rise of the field windings is deduced in terms involving the speed and the armature loss for a number of different machines, and a comparison is made of the temperature-rise as measured by resistance with that measured by thermometer.

TABLE OF CONTENTS.

1. HEATING TIME-CONSTANT.

When heat is generated at a uniform rate in a coil, and the rate of heat dissipation is proportional to the rise of temperature above the surrounding medium, the temperature-rise after a time t is given by :—

$$\theta_t = \theta\{1 - \epsilon^{-t/T}\}$$

In coils used on electrical machines and apparatus, however, the rate of generation of heat seldom remains constant, it being usual to keep either the current or the voltage constant. In the former case, the rate of heat generation increases with time owing to the increase in the resistance of the copper; whilst in the latter case the rate of heat generation decreases. The effects of these changes will now be considered.

Heating equation when current is kept constant.—

Let H = energy in joules to raise temperature of coil 1 degree C.,

W_1 = initial power generated in coil,

β = final temperature that would have been reached if power remained at W_1,

and T = corresponding time-constant,

then $TW_1 = \beta H$

$$\therefore H = \frac{TW_1}{\beta}$$

If θ_t be the temperature-rise after a time t secs., the power generated in the coil at that instant

$$= W_1(1 + \alpha\theta_t)$$

where α = temperature coefficient of resistance.

If k = power dissipated by coil per degree C. rise of temperature, then

$$W_1(1 + \alpha\theta_t)dt = k\theta_t dt + Hd\theta$$

If θ be the steady temperature-rise of coil when current is maintained constant, then

$$W_1(1 + \alpha\theta)dt = k\theta dt$$

$$\therefore k = \frac{W_1(1 + \alpha\theta)}{\theta}$$

Substituting for k and H in the above equation we have :—

$$W_1(1 + \alpha\theta_t)dt = \frac{W_1(1 + \alpha\theta)}{\theta}\theta dt + \frac{TW_1}{\beta}d\theta$$

from which $$\frac{dt}{T} = \frac{\theta}{\beta} \times \frac{d\theta}{\theta - \theta_t}$$

$$\therefore \frac{t}{T} = -\frac{\theta}{\beta}\log_\epsilon(\theta - \theta_t) + A$$

When $t = 0,\ \theta_t = 0;\ \therefore A = \frac{\theta}{\beta}\log_\epsilon \theta$

Hence $$\frac{t}{T} = \frac{\theta}{\beta}\log_\epsilon \frac{\theta}{\theta - \theta_t}$$

$$\therefore \theta_t = \theta\{1 - \epsilon^{-(t/T)(\beta/\theta)}\}$$

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

But $\quad k\beta = W_1$

and $\quad k\theta = W_1(1 + a\theta)$

$$\therefore \frac{\theta}{\beta} = 1 + a\theta$$

Hence $\quad \theta_t = \theta\{1 - \epsilon^{-t/[T(1+a\theta)]}\}$

Consequently the effect of increase of resistance is to increase both the temperature-rise and the time-constant by $(1 + a\theta)$, but the shape of the curve is not affected.

Heating equation when voltage is kept constant.—Using the same symbols as before, we have for a temperature-rise θ_t, power generated in coil $= W_1/(1 + a\theta_t)$ and $k = W_1/[\theta(1 + a\theta)]$.

$$\therefore \frac{W_1}{1 + a\theta_t}dt = \frac{W_1}{\theta(1 + a\theta)}\theta_t dt + \frac{TW_1}{\beta}d\theta$$

from which $dt\left[\frac{(\theta - \theta_t)\{1 + a(\theta + \theta_t)\}}{1 + a(\theta + \theta_t) + a^2\theta\theta_t}\right] = \frac{\theta T}{\beta}d\theta$

Since $a^2\theta\theta_t$ is negligibly small in comparison with $\{1 + a(\theta + \theta_t)\}$ for the temperature-rise permissible in coils, we have :—

$$dt(\theta - \theta_t) = \frac{\theta T}{\beta}d\theta$$

$$\therefore \theta_t = \theta\{1 - \epsilon^{-(t/T)(\beta/\theta)}\}$$

But $\quad k\beta = W_1$

and $\quad k\theta = \frac{W_1}{1 + a\theta}$

$$\therefore \frac{\theta}{\beta} = \frac{1}{1 + a\theta}$$

and $\quad \theta_t = \theta\{1 - \epsilon^{-t(1+a\theta)/T}\}$

Hence the effect of increase of resistance is to decrease the temperature-rise and the time-constant by $1/(1 + a\theta)$, but not to alter the shape of the curve.

Predetermination of the heating time-constant.—If the effect of the insulating covering on the wire and of the air in the interstices be neglected, the value of T can be calculated thus :—

Let N = number of turns on coil,
l = mean length per turn in cm,
a = sectional area of wire in cm^2,
ρ = resistance per cm cube of copper at initial temperature,
s = specific heat of copper,
D = density of copper,
i = current density in amperes per mm^2,
and I = current in amperes.

Then power generated in coil $= I^2\frac{\rho Nl}{a}$

But $T \times$ initial power generated $= 4\cdot2 \times$ number of calories to raise the temperature by β deg. C.

that is, $\quad TI^2\frac{\rho Nl}{a} = 4\cdot2NlaDs\beta$

$$\therefore T = \frac{4\cdot2Ds\beta}{\rho}\left(\frac{a}{I}\right)^2$$

Taking the average initial temperature as, say, 16° C.,

$$\rho = 1\cdot6 \times 10^{-6}\{1 + 0\cdot0043 \times 16\}$$
$$= 1\cdot71 \times 10^{-6}$$

Also, $D = 8\cdot9$, and $s = 0\cdot094$,

$$\therefore T = \frac{4\cdot2 \times 8\cdot9 \times 0\cdot094}{1\cdot71}10^6\left(\frac{1}{100i}\right)^2\beta$$
$$= \frac{205\beta}{i^2} \text{ seconds}$$
$$= \frac{3\cdot42\beta}{i^2} \text{ minutes}$$

It is often more convenient, however, to determine

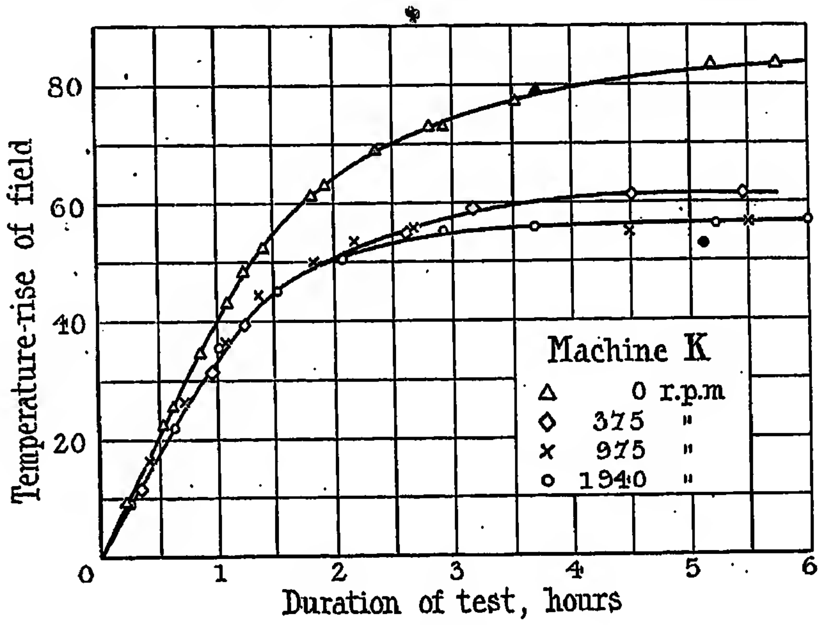

FIG. 1.

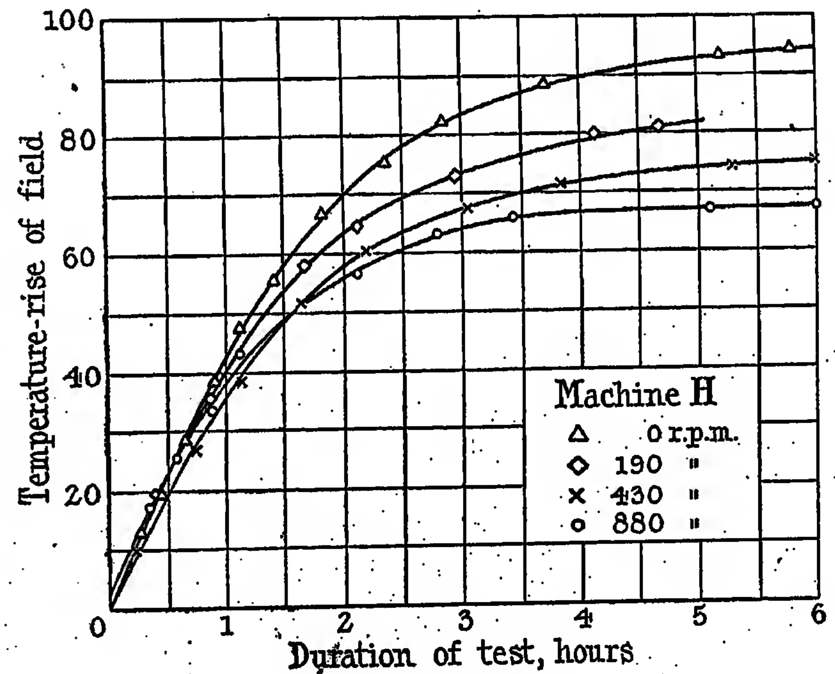

FIG. 2.

the temperature-rise per minute in terms of the current density; thus

$$\frac{\beta}{T} = \frac{i^2}{3\cdot42} = 0\cdot292i^2$$

If the current be maintained constant,

$$\beta = \frac{\theta}{1 + a\theta}$$

$$\therefore T(1 + a\theta) = \frac{3\cdot42\theta}{i^2}$$
$$= \frac{\theta}{\text{initial temp.-rise per min.}}$$

Similarly, if the voltage be maintained constant,

$$\beta = \theta(1 + a\theta)$$

$$\therefore \frac{T}{1 + a\theta} = \frac{3 \cdot 42\theta}{i^2}$$

$$= \frac{\theta}{\text{initial temp.-rise per min.}}$$

Comparison of test-results with the above expressions.—Tests were carried out on a number of coils, some being suspended in air and others being in position on the poles of d.c. machines. For convenience, the different coils have been designated A, B, etc., the particulars of the windings, etc., being given in the Appendix. It was found that fairly close agreement with the exponential law was obtained so long as the armatures were stationary. When the armatures were rotating, however, the shape of the heating curve for the field winding was modified very considerably. Typical cases of this effect are shown in Figs. 1 and 2.

The values of the actual heating time-constants for the coils have been determined from heating curves with armature stationary and compared with the values obtained from the above expressions, the results being incorporated in Table 1. The value of the time-constant was determined in each case by assuming values of θ and $T_{act.}$ and calculating the values of θ_t for different ratios of $t/T_{act.}$ in the equation $\theta_t = \theta\{1 - \epsilon^{-t/T_{act.}}\}$, the values of θ and $T_{act.}$ being varied to give values of θ_t as nearly as possible the same as those obtained from test. It was found impossible to get reliable and consistent results by drawing a tangent from the origin.

2. Cooling Tests on Field Coils.

Readings were taken of the resistances of field windings of machines F, G, H, I, J and K after the exciting currents had been switched off, the coils having attained steady temperatures. During the heating tests preceding these cooling tests, the armatures of all the machines were stationary. The resistances were measured at frequent intervals by a Post Office box, and the corresponding temperatures calculated. The difference of temperature between the coils and the air, after correction for any variation of the room temperature, has been plotted for each machine in Figs. 3, 4 and 5. It will be obvious that the cooling time-constant will not be affected by any variation in the resistance of the copper and may therefore be expected to agree with the value of T calculated in col. (10) of Table 1. On comparing the cooling curves with the nearest values obtainable from the expression

Table 1.

(1) Field coil	(2) Area of wire	(3) Heating (H) or cooling (C)	(4) Initial current density	(5) Initial temp.-rise per min.	(6) Temp.-rise by resistance (= θ deg. C.)	(7) $\theta \div$ initial temp.-rise per min.	(8) Heating or cooling time-constant from test	(9) Ratio Col. (8) / Col. (7)	(10) Value of T from col. (8)
	mm²		amps./mm²						
C	0·292	H *	2·19	1·4	40	28·6	55	1·92	63·8
	0·292	H †	1·54	0·691	24·7	35·8	69	1·93	63·0
D	0·3973	H *	4·0	4·67	75	16·1	33	2·05	43·0
	0·3973	H †	2·77	2·24	72·5	32·4	60	1·85	46·5
F	0·268	H †	2·09	1·28	69	53·9	82	1·52	64·2
	0·268	H †	1·868	1·02	54·5	53·5	78	1·46	64·1
	0·268	C	—	—	68·7	—	67	—	67·0
G	0·3167	H †	2·52	1·86	85	45·7	67	1·46	50·0
	0·3167	H †	2·21	1·43	67	46·9	62	1·32	48·9
	0·3167	H †	1·58	0·73	31	42·5	56	1·32	49·8
	0·3167	C	—	—	54·7	—	72	—	72·0
H	0·456	H †	1·865	1·015	75	73·9	112	1·515	86·1
	0·456	H †	1·318	0·507	35	69	104	1·51	91·2
	0·456	C	—	—	57·4	—	78	—	78·0
I	0·456	H †	2·195	1·405	86	61·2	99	1·62	73·6
	0·456	H †	1·865	1·015	68·5	67·5	115	1·70	90·2
	0·456	H †	1·318	0·507	32·5	64	106	1·66	93·8
	0·456	C	—	—	56·6	—	86	—	86·0
J	0·456	H †	2·04	1·215	75	61·7	100	1·65	76·9
	0·456	H †	1·37	0·548	41	74·8	108	1·445	92·7
	0·456	C	—	—	76·2	—	75	—	75·0
K	1·025	H †	2·0	1·165	84·5	72·6	86	1·187	64·3
	1·025	H †	1·51	0·664	58·5	87·9	107	1·218	86·5
	1·025	C	—	—	63·2	—	70	—	70·0

* Constant voltage. † Constant current.

$\theta_t = \theta\epsilon^{-t/T}$ it was found that agreement was fairly good during the first cooling period, but afterwards the divergence became comparatively large. The following figures for machines F and K are typical of the results obtained :—

Machine F (T = 67 mins.)			Machine K (T = 70 mins.)		
t	$\theta_t = \theta\epsilon^{-t/T}$	θ_t from curve	t	$\theta_t = \theta\epsilon^{-t/T}$	θ_t from curve
mins.			mins.		
0	76·2	76·2	0	63·2	63·2
6·7	62·1	61·8	7	57·1	57·0
13·4	56·2	55·2	14	51·7	51·2
26·8	46·0	45·0	28	42·3	41·1
47·0	34·1	33·5	49	31·3	30·7
67·0	25·3	25·4	70	23·22	23·3
100·5	15·2	18·2	105	13·97	16·7
134·0	9·3	14·7	140	8·51	13·9
167·5	5·63	12·6	175	5·18	10·5

To show more visibly how the rate of cooling varies with the temperature, the upper curves in Figs. 3, 4 and 5 have been drawn, the points being calculated from the fall in temperature in 10 minutes and the average temperature above air during that interval. It will be noted that the rate of cooling is not proportional to the temperature except during the initial period—a period that may on the average be taken to be equal to the cooling time-constant. Afterwards the ratio falls rapidly to become approximately steady once more at the lower temperatures. This variation in the rate of cooling cannot be due to alteration in the thermal conductivity of the insulating covering on the wire (see page 632) ; it is to some extent accounted for by the variation in the heating coefficient referred to on pages 637 and 645, though, for machines F, G, H and I, the variation of the heating coefficient (Fig. 20) is much less than the variation of the rate of cooling shown in the above figures. It would therefore appear that the effect under consideration is partly, if not mainly, due to a redistribution of temperature in the field winding and pole-cores caused by the different temperatures of these parts, and by the different heat emissivities of the various cooling surfaces.

The results obtained from these cooling tests have been included in Table 1, from which it is seen that the values of T derived from the cooling curves agree fairly closely with the values of T given in col. (10) for the corresponding maximum temperature.

Principal conclusions from the above considerations.—

(*a*) The heating and cooling curves for field coils are approximately exponential when the armature is stationary.

(*b*) The heating curve for the field coils with the armature rotating may deviate considerably from the exponential law—the higher the speed, the more square-shouldered the curve.

(*c*) The actual heating time-constant may be from 20 to 90 per cent greater than that calculated for the copper alone, the percentage increase being greater the smaller the size of the wire, the thicker its covering, and the larger the adjacent winding (if any).

(*d*) The heating time-constant for a coil with constant current is greater than that for the same coil with

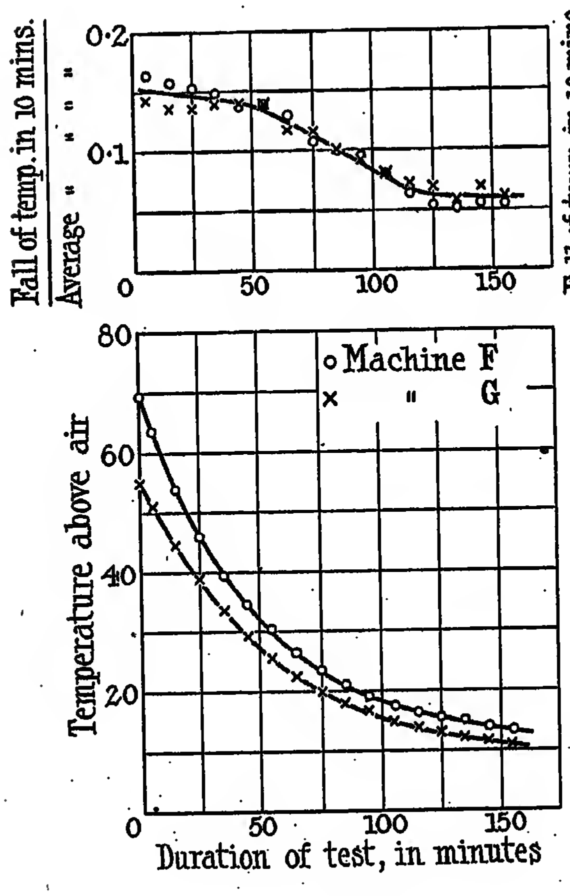

FIG. 3.

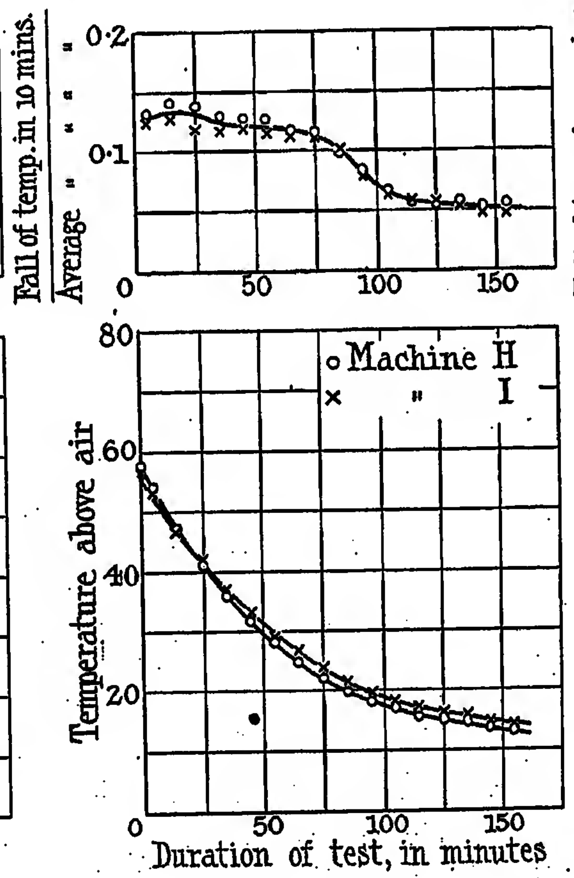

FIG. 4.

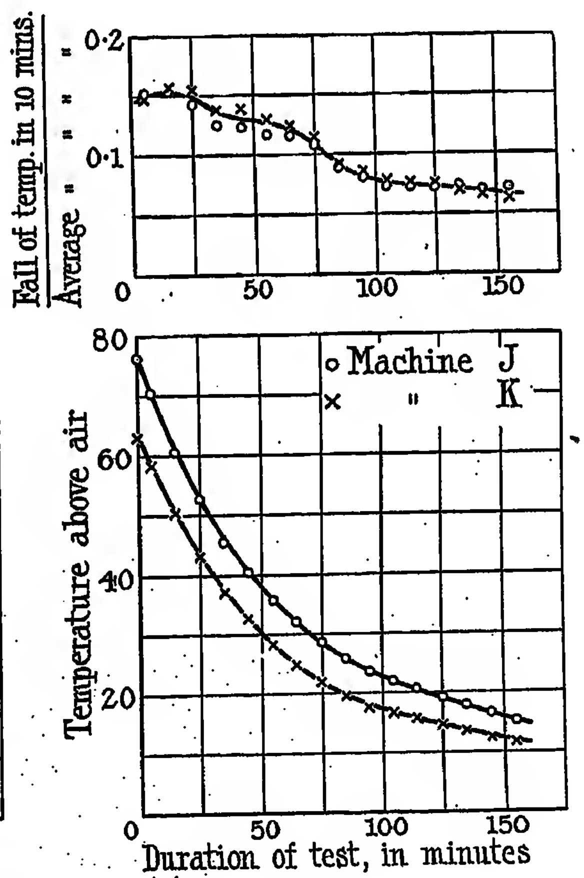

FIG. 5.

constant voltage, the difference being greater the higher the temperature-rise.

(*e*) The value of T, namely the time taken to attain steady temperature if the rate of heat generation remains at its initial value, is the same when calculated from constant-voltage and constant-current tests.

(*f*) The cooling time-constant is the same as the value of T calculated from the heating time-constant obtained from the constant-voltage or constant-current tests having roughly the same temperature-rise.

TABLE 2.

Current	Power	Temperature-rise by resistance	Temperature-rise per watt						
			By thermometer	By resistance	By thermo-couples				
					Inside	Three-quarter	Half	Quarter	Outside
amp.	watts	deg. C.	deg. C.	deg. C.	deg. C.	deg. C.	deg. C.	deg. C.	deg. C.
0·2	6·86	—	—	—	1·223	1·47	1·488	1·263	0·904
0·3	16·41	20·15	—	1·228	1·132	1·39	1·419	1·202	0·816
	16·65	20·75	—	1·248	1·13	1·386	1·416	1·206	0·823
	16·55	20·7	—	1·25	1·113	1·36	1·387	1·187	0·804
0·4	31·68	35·45	—	1·120	1·084	1·341	1·37	1·154	0·762
	31·9	35·8	—	1·122	1·08	1·339	1·37	1·165	0·768
0·5	53·75	57·6	—	1·072	1·02	1·27	1·293	1·09	0·706
	54·25	57·5	—	1·06	1·005	1·248	1·28	1·08	0·696
0·56	69·8	69·3	0·623	0·993	1·008	1·252	1·274	1·062	0·678
0·60	83·0	79·9	0·62	0·962	0·996	1·238	1·259	1·054	0·662

3. DISTRIBUTION OF TEMPERATURE IN A COIL.

A good deal of experimental work has already been done on this subject, but in most cases little appears to have been attempted except to give the bare results. In the discussion on Rayner's paper,* Sir Richard Glazebrook dealt fully with the theory of the subject and showed that the curves of temperature distribution should—on certain assumptions—follow the parabolic law; and curves from tests indicate that this is practically correct. He also made approximate calculations to determine various quantities affecting the temperature distribution. It was for the purpose of discovering if these factors could be determined more accurately and consistently that tests were made on coil A, which was fitted with five thermo-junctions of copper-constantan, two of the junctions being placed under and over the outer and inner layers respectively, and the other three junctions $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ of the distance along the section of the coil. The coil was impregnated after being wound the first time, but, owing to the junctions not having been properly placed, the coil had to be rewound. It was not re-impregnated, however. This probably accounts for the thermal conductivity of the insulation being of the same order as that of unimpregnated coils.

The coil was suspended in air and tested with different currents, and the temperatures of the junctions were measured by a calibrated galvanometer, each test being continued until the temperature became practically constant. The temperature-rise by resistance was also calculated, and in some cases the temperature-rise by thermometer was noted. Several of the tests were repeated to find how nearly the results agreed with each other. The temperature-rise per watt was calculated, and the results are given in Table 2.

The values of the temperature-rise per watt for the thermo-junctions have been plotted in Fig. 6, from

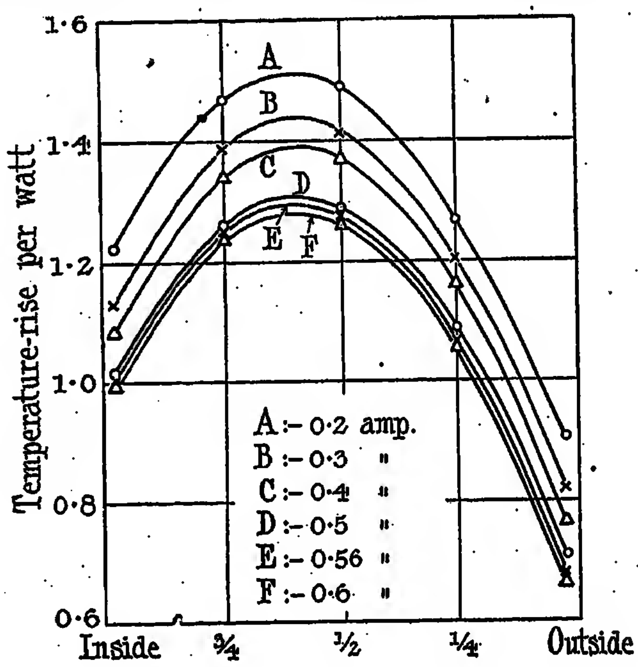

FIG. 6.

which it is evident that the temperature-rise per watt decreases appreciably with increasing values of the temperature-rise, but that the distribution of temperature and, therefore, the thermal conductivity of the insulation are almost independent of the temperature-rise.

The above results will now be analysed on the basis of Glazebrook's theory.

* *Journal I.E.E.*, 1905, vol. 34, p. 613.

If w = power in watts generated per cm³ of the coil,
W = total power generated in coil,
V = volume of coil in cm³,
θ_x = temperature-rise at distance x cm from the line of maximum temperature,
θ_m = maximum temperature-rise,
k = thermal conductivity of coil in watts per cm cube,
k_c = thermal conductivity of copper in watts per cm cube,
k_i = thermal conductivity of insulation in watts per cm cube,
a = depth of copper per cm depth of coil,

then
$$\frac{1}{k} = \frac{a}{k_c} + \frac{1-a}{k_i}$$
$$\therefore\ k_i = \frac{kk_c(1-a)}{k_c - ka} = k(1-a)$$
since ka is small compared with k_c, as shown below.

Thermal conductivity of copper $= k_c = 3\cdot 02$ watts per cm cube.

But the average value of k is about $0\cdot 004$, so that ka is obviously negligible compared with k_c.

By a trial-and-error method, a value of a giving the closest approximation to the values of θ_x/W in Table 2 can be determined for each value of the current. Table 3 gives results typical of those obtained, showing how very closely the test values agree with those calculated from the parabolic law.

It was thought that instead of allowing for the thickness of the insulation on the wire, more consistent values for the effective thermal conductivity might be obtained by taking account of the space factor; thus if

F_s = space factor of copper,
A = sectional area of coil,

and a_e = depth of copper per cm depth of coil for a square wire of equivalent area,

TABLE 3.

Junction	x	Current 0·6 amp.					Current 0·4 amp.				
		a	$\frac{\theta_m}{W}$	$\frac{\theta_m}{W} - ax^2$	θ_x/W by test	θ_x/W by Walker's expression	a	$\frac{\theta_m}{W}$	$\frac{\theta_m}{W} - ax^2$	θ_x/W by test	θ_x/W by Walker's expression
Outside	2·62	0·0911	1·28	0·655	0·662	0·663	0·0931	1·39	0·75	0·764	0·755
$\frac{1}{4}$	1·575	0·0911	1·28	1·053	1·054	1·050	0·0931	1·39	1·159	1·159	1·158
$\frac{1}{2}$	0·45	0·0911	1·28	1·261	1·259	1·26	0·0931	1·39	1·371	1·37	1·369
$\frac{3}{4}$	0·675	0·0911	1·28	1·238	1·238	1·237	0·0931	1·39	1·347	1·34	1·347
Inside	1·72	0·0911	1·28	1·01	0·996	1·0	0·0931	1·39	1·114	1·082	1·108

It was shown by Glazebrook that
$$\theta_m - \theta_x = \frac{w}{2k}x^2$$
$$= \frac{W}{2Vk}x^2 = bx^2$$
where
$$b = \frac{W}{2Vk}$$
or
$$\frac{\theta_m}{W} - \frac{\theta_x}{W} = \frac{x^2}{2Vk} = ax^2$$
where
$$a = \frac{1}{2Vk} = \frac{b}{W}$$

Hence $\theta_x = \theta_m - bx^2$, or $\theta_x/W = (\theta_m/W) - ax^2$.

For the coil under consideration:—

Average depth of coil .. .. = 4·5 cm,
Depth of line of maximum temperature from outside .. = 0·6 × depth of coil,
= 2·7 cm,
Volume of coil .. .. .. = 2 540 cm³,
Diameter of wire (bare) .. = 0·0545 cm,
Diameter of wire (d.c.c.) .. = 0·08 cm,
$$\therefore\ a = \frac{0\cdot 0545}{0\cdot 08} = 0\cdot 68.$$

then Aa_e^2 = total sectional area of copper,
$= F_sA$
$\therefore\ a_e = \sqrt{F_s}$

If k_{ie} = effective thermal conductivity of the insulation (including air space) in watts per cm cube,

then $k_{ie} = k(1 - a_e)$,
$= k(1 - \sqrt{F_s})$.

In order to check the values of the thermal conductivity obtained from coil A, all the curves given by Rayner * that appeared reliable were examined, and the value of $b(= aW)$ giving the nearest approximation to the whole curve was determined in each case.

The values obtained, together with the calculated values of k_i and k_{ie}, are given in Table 4. Rayner's coils are designated by the same figures as in his original paper.

The wires in all the above coils, except 4B, were double-cotton-covered, 4B being single-cotton-covered; and only 2A and 2B had been impregnated.

From the table it is seen that :—

(a) The values of the thermal conductivity of the insulation calculated from the space factor are more consistent than those obtained by simply allowing for the covering on the wire.

* *Loc. cit.*

(b) The value of the effective thermal conductivity of the insulation may be taken approximately as 0·001 for an unimpregnated coil and 0·002 for a coil that is impregnated. The space factor allows—at least to some extent—for the variation in the tightness with which coils may be wound.

The influence of different kinds of insulating coverings on the wire and of impregnation of the coil upon the distribution of temperature was dealt with by Rayner in the *Electrician* (1914, vol. 72, p. 702), but as no dimensions were given it was not possible to subject the results to the above analysis.

An alternative method of calculating the temperature at a distance x from the line of maximum temperature was given by Symons and Walker,* but the expression has been modified slightly in Miles Walker's "Diagnosing of Troubles in Electrical Machines" (page 62).

If θ_a be the air temperature, then using the same symbols as above we can write the expression in the form

$$(\theta_x + \theta_a + 235) = (\theta_m + \theta_a + 235) \cos px$$

where $p = I_x \sqrt{\left(\dfrac{1\cdot 6 \times 10^{-6} \times \sigma \times \beta}{k_i \times 235}\right)}$

σ = copper space-factor,

β = thickness of insulation per cm depth of winding,

$= 1 - \alpha$,

k_i = thermal conductivity of the insulation in watts per cm cube,

$I_x = i \sqrt{\left(\dfrac{l}{l+d}\right)}$

i = current density in amps. per cm^2,

l = length of bobbin in cm,

and d = depth of winding in cm.

TABLE 4.

Coil	a	b	k Author	k Glazebrook	Thermal conductivity of insulation k_i	k_{ie}	k_i by Walker's expression	k_i by Glazebrook	Remarks
			$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$	
A	0·097	—	2·03	—	0·65	1·05	0·52	—	0·2 amp.
A	0·095	—	2·07	—	0·662	1·07	0·473	—	0·3 amp.
A	0·0931	—	2·12	—	0·678	1·1	0·485	—	0·4 amp.
A	0·089	—	2·21	—	0·706	1·145	0·466	—	0·5 amp.
A	0·0939	—	2·10	—	0·672	1·09	0·50	—	0·56 amp.
A	0·0911	—	2·16	—	0·691	1·12	0·51	—	0·6 amp.
B	0·155	—	3·94	—	0·85	1·36	—	—	Constant current } Coil suspended in air
B	0·150	—	4·07	—	0·88	1·4	—	—	Constant voltage } Coil suspended in air
B	0·16	—	3·82	—	0·825	1·32	0·482	—	Air velocity = 0 m/sec. (p.639)
B	0·175	—	3·5	—	0·756	1·21	0·479	—	Air velocity = 0·326 m/sec.
B	0·185	—	3·3	—	0·713	1·14	0·426	—	Air velocity = 0·46 m/sec.
B	0·17	—	3·6	—	0·777	1·24	0·471	—	Air velocity = 0·683 m/sec.
B	0·17	—	3·6	—	0·777	1·24	0·473	—	Air velocity = 1·183 m/sec.
B	0·168	—	3·64	—	0·786	1·26	0·498	—	Air velocity = 1·65 m/sec.
B	0·14	—	4·36	—	0·94	1·5	—	—	Air velocity = 0 m/sec. (p.638)
B	0·15	—	4·07	—	0·88	1·4	—	—	Air velocity = 0·535 m/sec.
B	0·15	—	4·07	—	0·88	1·4	—	—	Air velocity = 0·814 m/sec.
B	0·16	—	3·82	—	0·825	1·32	—	—	Air velocity = 2·16 m/sec.
B	0·162	—	3·78	—	0·817	1·30	—	—	Air velocity = 3·22 m/sec.
2A	—	1·8	8·0	7·83	1·26	2·10	1·0	—	} Coils thoroughly impregnated
2B	—	1·75	8·12	8·35	1·28	2·13	0·964	1·34	} Coils thoroughly impregnated
4B	—	1·2	6·08	5·55	0·78	1·98	0·812	—	s.c.c.
5	—	1·3	4·27	4·4	0·427	0·947	0·352	0·354	
7B	—	2·4	1·93	1·89	0·232	0·67	0·176	0·354	
7C	—	3·9	2·21	1·7	0·265	0·766	0·215	—	Varnished on outside only
8A	—	1·95	4·05	4·41	0·47	1·17	0·447	1·97	
8B	—	4·3	3·98	4·96	0·462	1·19	0·487	—	

The values of θ_x for a number of different coils were calculated from the most suitable values of p and θ_m for each case, and were found to be in close agreement with those given by the thermo-junctions. The figures for coil A with 0·6 and 0·4 amp. are given in Table 3. From the various values of p, the corresponding values of k_i have been calculated by means of the above expression and incorporated in Table 4. The expression,

* *Journal I.E.E.*, 1912, vol. 48, p. 694.

however, is much more cumbersome than that of Glazebrook.

The value of β may be determined (*a*) by allowing for the thickness of the covering on the wire, (*b*) by finding the total depth of copper from the number of layers and the diameter of the wire, or (*c*) by calculating the effective thickness of the insulation from the space factor of the copper as referred to on page 633. Unfortunately, these three methods when applied to the coils under consideration give inconsistent results, as will be seen from Table 5.

TABLE 5.

Values of β.

Coil	First method	Second method	Third method
A	0·32	0·516	0·518
B	0·216	0·269	0·345
2A and 2B	0·157	0·148	0·262
4B	0·129	0·232	0·326
5	0·10	0·106	0·222
7B and 7C	0·12	0·18	0·347
8A and 8B	0·116	0·288	0·293

The third method would be expected to give a larger value than those obtained from the first and second methods. The second method appears to be the least consistent; consequently the values of the thermal conductivity have been based on the first and third methods, i.e. the values of k_i in Table 4 are based upon the values of β given in the first column of Table 5, whilst those of k_{ie} are based upon the last column of Table 5.

A comparison of the values of k_i and k_{ie} given in Table 4 indicates that those for k_{ie} are more consistent than those for k_i. It also shows that the values of k_i calculated by the parabolic law are a little more consistent than those based upon the formula suggested by Miles Walker.

It follows from the above table that the temperature-rise at a distance x from the line of maximum temperature is given fairly closely by the expression

$$\theta_x = \theta_m - \frac{W}{2Vk}x^2$$

$$= \theta_m - \frac{W}{2V} \times \frac{1 - \sqrt{F_s}}{k_{ie}}x^2$$

where $k_{ie} = 0{\cdot}001$ for unimpregnated coils with cotton-covered wire,

$= 0{\cdot}002$ for impregnated coils with cotton-covered wire.

This expression may be still further simplified thus :—

$$\frac{W}{V} = \frac{I^2R}{lA} = \frac{I^2\rho lN}{a} \times \frac{F_s}{lNa}$$

$$= i^2\rho F_s$$

where l = mean length per turn,

i = current density in amps per cm^2,

ρ = specific resistance of copper at average temperature of coil, and may be taken as 2 microhms per cm cube.

Hence $\theta_x = \theta_m - \frac{1}{2}i^2 \times 2 \times 10^{-6}F_s \times \frac{1 - \sqrt{F_s}}{k_{ie}}x^2$

$= \theta_m - 10^{-3} \times i^2F_s(1 - \sqrt{F_s})x^2$ for unimpregnated coils with cotton-covered wire,

$= \theta_m - \frac{1}{2} \times 10^{-3}i^2F_s(1 - \sqrt{F_s})x^2$ for impregnated coils with cotton-covered wire.

4. Relation between the Maximum and the Mean Temperatures.

If the temperature distribution between the outside and inside of a coil be assumed parabolic, i.e. $\theta_x = \theta_m - bx^2$, and if d be the depth of the coil in cm, and x_1 and x_2 be the distances from the line of maximum temperature to the outside and inside respectively, then $d = x_1 + x_2$, and the average temperature across the section is given by :—

$$\theta_{av.} = \frac{1}{x_1 + x_2}\int_{-x_2}^{x_1}(\theta_m - bx^2)dx$$

$$= \theta_m - \frac{b}{3}\left(\frac{x_1^3 + x_2^3}{x_1 + x_2}\right)$$

$$\therefore \theta_m - \theta_{av.} = \frac{b}{3}\left(\frac{x_1^3 + x_2^3}{x_1 + x_2}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

From this expression Table 6 has been calculated for the various coils already considered.

The majority of the values for $(\theta_m - \theta_{av.})$ calculated from the above expression are much smaller than those obtained by subtracting the temperature-rise by resistance from the maximum temperature-rise by thermo-couples. That this should be the case is evident from most of the curves given by Rayner for thermo-couples placed longitudinally along the line of maximum temperature. Most of the curves thus obtained were parabolic and indicate that some heat at least was being dissipated from the cheeks of the coils. They also showed that the difference of temperature between the centre and the ends of the coils depends to some extent upon the ratio of the length to the depth of the coil. To allow for this factor in some way, the calculated values of $(\theta_m - \theta_{av.})$ have been multiplied by $\sqrt{(l/d)}$ to give the figures in the last column of Table 6. Most of the values agree fairly well with the values deduced from the tests. It should be mentioned that there appeared to be a discrepancy in some of Rayner's readings for the temperature-rise by resistance.

It has been observed that in the majority of coils the line of maximum temperature is at about 0·6 of the depth from the outer surface, so that

$$\theta_m - \theta_{av.} = \frac{b}{3}0{\cdot}28d^2 = \frac{W}{2Vk} \times \frac{0{\cdot}28}{3}d^2$$

$$= 0{\cdot}0467\frac{W}{V} \times \frac{d^2(1 - \sqrt{F_s})}{k_{ie}} \quad . \quad . \quad (2)$$

TABLE 6.

Coil	$\frac{x_2}{d}$	$\frac{x_1^3+x_2^3}{x_1+x_2}$	d	b	$\theta_m-\theta_{av.} = \frac{b}{3}\left(\frac{x_1^3+x_2^3}{x_1+x_2}\right)$	$\theta_m-\theta_{av.}$ from test	Length of coil, l	$\sqrt{\frac{l}{d}}$	Calculated value of $(\theta_m-\theta_{av.}) \times \sqrt{\frac{l}{d}}$
2A	0·4	$0·28d^2$	7·62	1·9	10·3	21·5	17·8	1·53	15·8
2B	0·4	$0·28d^2$	7·62	1·75	9·47	20·0	17·8	1·53	14·5
4B	0·2	$0·521d^2$	5·08	1·2	5·3	4·1	15·3	1·73	9·2
5	0·46	$0·255d^2$	8·38	1·3	7·8	7·5	21·6	1·61	12·6
7B	0·36	$0·3087d^2$	5·71	2·4	8·05	16·4	26·6	2·16	16·8
7C	0·36	$0·3087d^2$	5·71	3·9	13·1	21·7	26·6	2·16	28·3
8A	0·36	$0·3087d^2$	5·71	1·95	6·56	16·0	32·4	2·38	15·6
8B	0·36	$0·3087d^2$	5·71	4·3	14·4	36·0	32·4	2·38	34·3
A (0·3A)	0·4	$0·28d^2$	4·5	1·57	2·97	3·4	9·0	1·41	4·2
A (0·4A)	0·4	$0·28d^2$	4·5	2·96	5·6	8·5	9·0	1·41	7·9
A (0·5A)	0·4	$0·28d^2$	4·5	4·81	9·1	13·0	9·0	1·41	12·8
A (0·56A)	0·4	$0·28d^2$	4·5	6·56	12·4	21·1	9·0	1·41	17·5
A (0·6A)	0·4	$0·28d^2$	4·5	7·56	14·3	26·3	9·0	1·41	20·2

TABLE 7.

Coil	$\sqrt{\frac{l}{d}}$	Value of k_{ts} assumed	$(\theta_m-\theta_{av.})$				$(\theta_m-\theta_{av.})$ from (3) $\times \sqrt{\frac{l}{d}}$
			By test	From (1)	From (2)	From (3)	
1α	1·34	0·001	17·3	—	11·4	8·9	11·9
1β	1·34	0·001	15·5	—	13·0	9·4	12·6
1γB	1·34	0·001	13·4	—	16·6	12·05	16·1
1γC	1·34	0·001	12·7	—	13·8	10·4	13·9
1γD	1·34	0·001	7·3	—	11·2	8·75	11·7
1γE	1·34	0·001	5·8	—	9·0	7·25	9·7
1γF	1·34	0·001	16·4	—	14·8	11·7	15·7
1δ	1·34	0·002	8·0	—	6·5	5·85	7·85
2A	1·53	(d.c.c., berrited) 0·002	21·5	10·3	10·2	9·5	14·5
2B	1·53	(impregnated) 0·002	20·0	9·47	10·1	9·5	14·5
4B	1·73	(impregnated) 0·002 (s.c.c.)	4·1	5·3 ($x_2 = 0·2d$)	2·83	3·27	5·65
5	1·61	0·001	7·5	7·8	8·1	9·7	15·6
7A	2·16	0·001	9·6	—	5·23	4·65	10·1
7B	2·16	0·001	16·4	8·05	4·91	4·65	10·1
7C	2·16	0·001	21·7	13·1	9·12	7·3	15·8
8A	2·38	0·001	16·0	6·56	7·07	7·5	17·8
8B	2·38	0·001	36·0	14·4	15·3	13·7	32·6
8C	2·38	0·001	22·4	—	7·51	7·25	17·3
8D	2·38	0·001	25·3	—	6·5	6·35	15·1
A (0·3A)	1·41	0·001	3·4	2·97	3·2	4·05	5·7
A (0·4A)	1·41	0·001	8·5	5·6	6·14	7·2	10·1
A (0·5A)	1·41	0·001	13·0	9·1	10·4	11·3	15·9
A (0·56A)	1·41	0·001	21·1	12·4	13·5	14·1	19·9
A (0·6A)	1·41	0·001	26·3	14·3	16·0	16·2	22·8

But it has already been shown that

$$\frac{W}{V} = i^2 \rho F_s$$

$$\therefore\ \theta_m - \theta_{av.} = \tfrac{1}{2} i^2 \times 2 \times 10^{-6} F_s \frac{1 - \sqrt{F_s}}{k_{ie}} \times \frac{0 \cdot 28}{3} d^2$$

$$= 0 \cdot 1 \times 10^{-6} \frac{i^2 d^2 F_s (1 - \sqrt{F_s})}{k_{ie}} \quad . \quad . \quad (3)$$

To show how the values derived from Equations (1), (2) and (3) agree with each other, Table 7 has been compiled, mainly from the data in Rayner's paper.

A comparison of the different columns shows that the values calculated by the three expressions agree moderately well, and when multiplied by such a factor as $\sqrt{(l/d)}$ they give approximately the difference between the maximum temperature-rise and the temperature-rise measured by resistance. Since Equation (3) is undoubtedly the simplest to apply in the majority of cases, we can state that :—

Maximum temperature-rise — Average temperature-rise

$$= i^2 d^2 F_s (1 - \sqrt{F_s}) \sqrt{\frac{l}{d}} \times 10^{-4}$$

for unimpregnated coil with cotton-covered wire,

and $$= 0 \cdot 5 i^2 d^2 F_s (1 - \sqrt{F_s}) \sqrt{\frac{l}{d}} \times 10^{-4}$$

for impregnated coil with cotton-covered wire.

The factor 10^{-4} can be eliminated by expressing the current density in amperes per mm².

5. Variation of Temperature-rise per Watt with Temperature-rise.

The figures given in Table 2 show that the higher the temperature-rise, the lower the temperature-rise per watt. This result has also been observed by other experimenters. For instance, curves were given by Lister * for six different field coils, the temperature-rise being measured by resistance. Coils I, II, III and IV were suspended in air, whilst coils V and VI were on their machines, the armatures of which were stationary. These curves have been analysed and found to agree very closely with the expression:—

Temp.-rise per watt per dm² of total surface

$$= \frac{\theta A}{W} = \frac{c}{1 + a\theta}$$

where c and a have the following values :—

	Coils I and IV	Coils II and III	Coil V	Coil VI
c	17·5	19·55	16·25	20·2
a	0·0036	0·0038	0·0023	0·0033

The values of the temperature-rise per watt (by resistance) given in Table 2 have also been analysed in a similar way, and are found to be represented by

$$\frac{\theta}{W} = \frac{1 \cdot 35}{1 + 0 \cdot 005\theta} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

or $$\frac{\theta A}{W} = \frac{22 \cdot 5}{1 + 0 \cdot 005\theta}$$

where A represents the total surface of the coil, namely, 16·7 dm².

On page 645 are given the results derived from tests on six different machines with their armatures stationary, for which the value of a in the above expression is found to vary from 0·0026 to as much as 0·03, the larger values being obtained for the open-type machines.

It is of interest to compare the above results with those obtained by other investigators. Let us first consider Stefan's law of radiation, viz. :—

Heat lost per sec. $\propto (T_2^4 - T_1^4)$

i.e. $$W = \frac{1}{k}(T_2 - T_1)(T_2 + T_1)(T_2^2 + T_1^2)$$

where T_2 = absolute temperature of the hot body,
T_1 = absolute temperature of the air,
and k = a constant for a given surface.

Then temperature-rise per watt

$$= \frac{\theta}{W} = \frac{T_2 - T_1}{W}$$

$$= \frac{k}{(T_2 + T_1)(T_2^2 + T_1^2)}$$

The best value of k for coil A is found to be 1·4; then taking the air temperature as 15° C. we have

$$\frac{\theta}{W} = \frac{1 \cdot 4}{(T_2 + 288)\{T_2^2 + (288)^2\}} \quad . \quad . \quad . \quad (5)$$

The values derived for coil A from this expression are given in Table 8. It is found, however, that these values are practically the same as those given by

$$\frac{\theta}{W} = \frac{1 \cdot 4}{1 + 0 \cdot 006\theta}$$

Flack, Griffiths and Hill,* in a paper on "Rate of Loss of Heat," gave the following expression for the cooling effect of still air :—

Watts per dm² of total surface

$$= 0 \cdot 027(1 + 0 \cdot 002\theta_a)\theta^{5/4}$$

where θ_a = air temperature,
and θ = temperature-rise.

The effect of θ_a can be neglected in the present discussion since the air temperature was always within the limits of 12° C. and 20° C.; hence this expression may be modified thus :—

$$\text{Temperature-rise per watt} = \frac{\theta}{W} = \frac{k_1}{\theta^{1/4}} \quad . \quad . \quad (6)$$

where k_1 is a constant for a given surface.

The results calculated from this expression after

* *Journal I.E.E.*, 1907, vol. 38, p. 399.

* See *Electrician*, 1915, vol. 76, p. 411.

having determined the best value of k_1 for coil A, namely 2·84, agree fairly closely with those obtained from test, as will be seen from Table 8.

In an article* on "Heat Losses in Heat Transmission," W. L. Cathcart refers to Peclet's empirical formulæ based on tests for temperature-rises between 25° C. and 65° C. with an average air temperature of 12° C. The heat loss due to contact of the air with surface of coil was found to be proportional to $\theta^{1\cdot 23}$, a result practically identical with the expression just dealt with. The loss of heat by radiation was found to be proportional to $(b^\theta - 1)$,

that is $$W = m(b^\theta - 1)$$

where b = a constant (1·0077 for metric units), m = a factor depending upon the nature of the surface.

This expression can be written thus :—

$$W = m\{(1 + 0\cdot 0077)^\theta - 1\}$$
$$= m\theta \times 0\cdot 0077[1 + \tfrac{1}{2}(\theta - 1)0\cdot 0077]$$

for the range of θ permissible in windings.

$$\therefore \frac{\theta}{W} = \frac{m_1}{1 + \frac{1}{2}(\theta - 1)0\cdot 0077}$$
$$\equiv \frac{m_1}{1 + 0\cdot 00385\theta}$$

This is obviously of the same form as Equation (4) above; and the coefficient 0·00385 agrees very closely with the values calculated for Lister's coils I to IV.

TABLE 8.

Values of θ/W.

θ° C.	From curve of test-results	From (4)	From (5)	From (6)
20·45	1·238	1·225	1·26	1·338
35·65	1·14	1·148	1·16	1·17
57·5	1·05	1·049	1·045	1·033
69·3	0·995	1·002	0·985	0·985
79·9	0·962	0·964	0·933	0·951

By comparing the figures deduced from the different expressions, it is seen that those based upon the simple expression

$$\frac{\theta}{W} = \frac{c}{1 + a\theta}$$

are nearer the actual values in the particular case considered, namely a coil suspended in air. The different values of a that have been observed for field coils in position on the poles is probably due to the heat being dissipated from a number of different surfaces, such as the external surfaces of the coil, the exposed surfaces of the poles and yoke, etc., all of which are at different temperatures. Also, the relative amounts of heat dissipated by these different surfaces vary with the type of machine.

* *Cassier's Magazine*, December, 1915.

6. Effect of Forced Draught upon Temperature-rise of a Coil.

Coil B was enclosed in a wooden box with holes, one at each end. A fan was fitted at one end to draw the air over and around the coil, the velocity of the air being measured at the input end by means of a Negretti and Zambra anemometer. A mesh was placed over the inner end of the inlet pipe to reduce any air eddies that might be formed.

The coil had 36 layers, and thermo-junctions were arranged: 1, 8, 9, 9, 8, 1. Temperature readings were taken for different air velocities, and the temperature-rise after 3 hours was determined in each case. The temperature-rise per watt was then calculated, the values being plotted in Fig. 7.

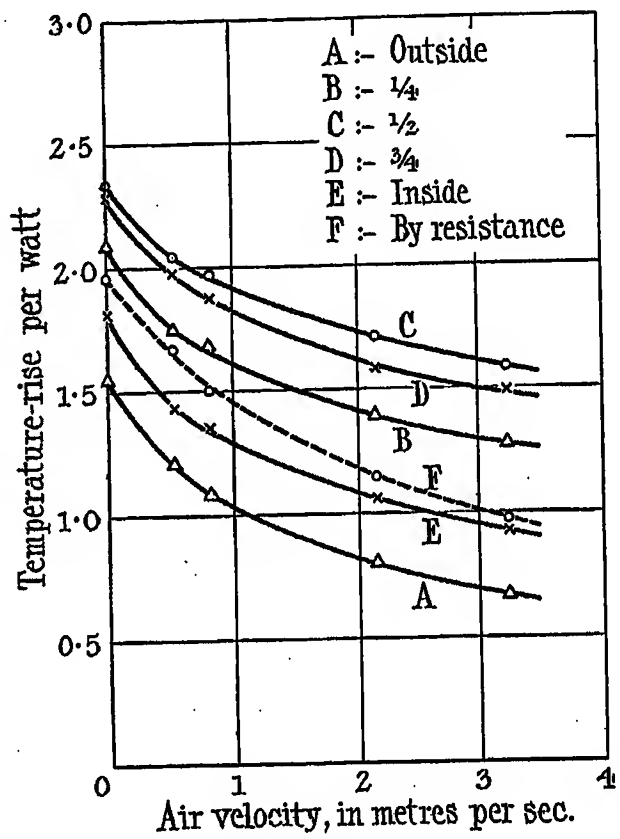

FIG. 7.

From the curve for temperature-rise by resistance it is found that

$$\frac{\theta}{W} = \frac{1\cdot 96}{1 + 0\cdot 325v}$$

where v = inlet velocity of air in m/sec.; and temperature-rise per watt per dm² $= \dfrac{\theta A}{W} = \dfrac{5\cdot 44}{1 + 0\cdot 325v}$, since $A = 2\cdot 78$ dm² for *external* cylindrical surface of coil.

For the outside thermo-junction we have.

$$\frac{\theta_0 A}{W} = \frac{4\cdot 28}{1 + 0\cdot 44v}$$

whilst for the centre of the coil the curve for $(\theta_m A)/W$ is intermediate between

$$6\cdot 56/(1 + 0\cdot 18v) \quad \text{and} \quad 6\cdot 56/(1 + 0\cdot 25\sqrt{v})$$

These results show that the temperature-rise of the

outside of a coil ventilated in the above manner is relatively much more affected than that of the centre of the coil.

An arrangement shown diagrammatically in Fig. 8 was next constructed, whereby the air could be made to impinge at a high velocity at four points on the surface of the coil, the velocity again being measured by an anemometer. The diameter of the tube where the velocity was measured was 7·5 cm in both of these experiments, so that the volume of air per second was 0·00442 × velocity in m/sec. As the total area of the nozzles was about 3·5 cm², the velocity of the air at the nozzles was 12·6 times that measured.

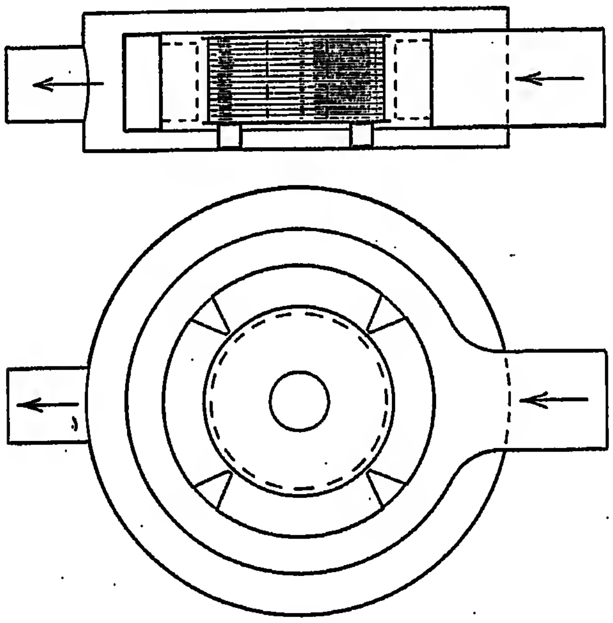

FIG. 8.

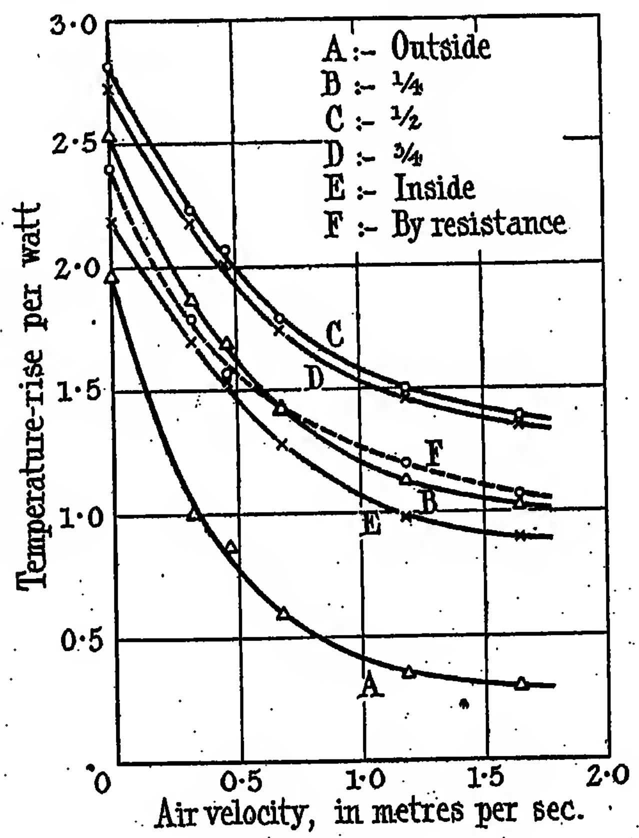

FIG. 9.

The results are plotted in Fig. 9, from which it is seen that for velocities up to about 1 m/sec. the temperature-rise per watt decreases very rapidly.

The curve for the temperature-rise by resistance is found to be intermediate between

$$\frac{\theta A}{W} = \frac{6\cdot67}{1 + 0\cdot86v} \quad \text{and} \quad \frac{\theta A}{W} = \frac{6\cdot67}{1 + 0\cdot935\sqrt{v}}$$

v being the velocity actually measured.

For the outside thermo-junction the temperature-rise agrees fairly closely with

$$\frac{\theta_0 A}{W} = \frac{5\cdot44}{1 + 4v^{1\cdot5}}$$

and the maximum temperature-rise is given approximately by

$$\frac{\theta_m A}{W} = \frac{7\cdot8}{1 + 0\cdot75v}$$

It may again be stated that A in the above expressions is the external cylindrical surface only.

A comparison of the results obtained in the above tests indicates the great improvement that may be effected by arranging for the air to impinge at a high velocity on the surface to be cooled, but that there is not much advantage in increasing the velocity beyond a certain value.

In the paper by Symons and Walker already referred to, curves are given for the temperature-rise of a coil and of a brass cylinder for different air velocities up to 3·5 m/sec., the results being expressed by

$$\frac{\theta A}{W} = \frac{9\cdot1}{1 + 0\cdot78v^2} \text{ (for brass cylinder)},$$

$$= \frac{9\cdot1}{1 + 0\cdot54v^2} \text{ (for coil of cotton-covered wire)}.$$

In these tests the air was blown on to the coil from two diametrically opposite sides; also the cylinder and coil were comparatively shallow.

On the other hand, Flack, Griffiths and Hill found the cooling effect of wind for velocities up to 15·6 m/sec. to be given by

$$\frac{\theta A}{W} = \frac{8\cdot8}{1 + 2\sqrt{v}}$$

whilst J. A. Hughes, in dealing with "Cooling of Cylinders in Stream of Air," * gives the loss of heat from different cylindrical tubes at 100° C. as proportional to v^n, where n varies between 0·55 for the smallest cylinder and 0·98 for the largest.

The above results are sufficient to show how the effect of air velocity may vary considerably with the manner in which the air impinges on a coil, and with the depth and the perimeter of the coil. It would appear that the only satisfactory method of deducing a reliable formula is from tests on a coil or a machine as similar as possible to the one under consideration.

7. A New Arrangement for Measuring the Average Temperature-rise of Field Windings.

The usual method of measuring the average temperature-rise of a winding is to determine by the voltammeter method or by a Post Office box the resistances

* *Philosophical Magazine*, 1916, ser. 6, vol. 31, p. 118.

R_1 and R_2 when cold and hot, respectively. Then if θ_1 and θ_2 be the initial and final temperatures respectively,

$$(\theta_2 - \theta_1) = (234 \cdot 5 + \theta_1)\frac{R_2 - R_1}{R_1}$$

The Post Office box method has the disadvantage that readings cannot be taken without stopping the machine, and even if this is done fairly quickly the temperature may have changed appreciably in the interval. Furthermore, there is always the liability of applying excessive voltage to the resistance box. The volt-ammeter method in the hands of an experienced person gives reasonably good results if the supply voltage is perfectly steady. If the voltage is fluctuating it is almost impossible to obtain reliable figures, and it was with the object of overcoming this difficulty that the author tried other arrangements and found the following method to work extremely satisfactorily.

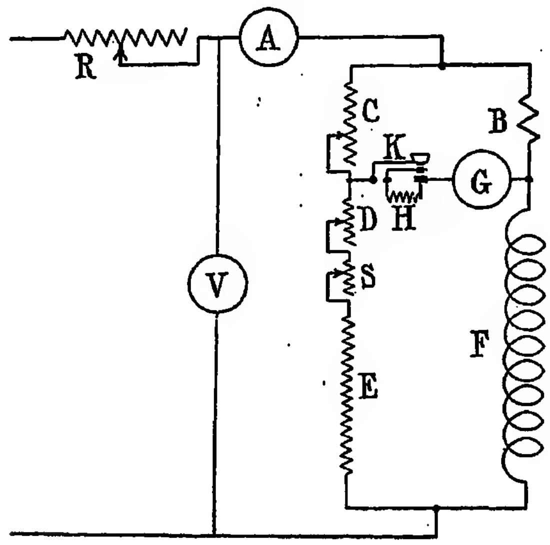

FIG. 10.

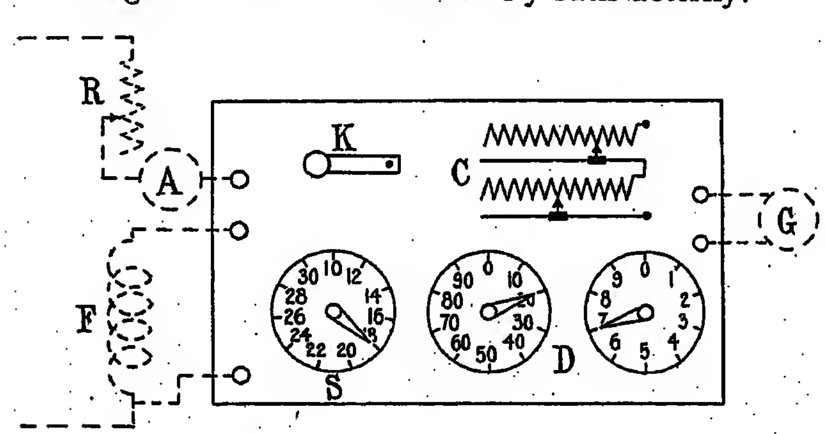

FIG. 11.

The connections are shown in Fig. 10, and Fig. 11 gives the appearance of the apparatus as constructed. F is the shunt winding and R the shunt regulator. E is a resistance of 3 000 ohms, B a shunt of about 0·5 ohm, C a variable resistance, and D a resistance arranged with two dials, the values of the steps being calculated so that the dials give the temperature-rise directly. S is a compensating resistance to allow for variations of the initial temperature. Dial S in Fig. 11 is arranged in steps of 2 degrees C. between 10° C. and 30° C. This subdivision reduces to quite a negligible amount any error due to variation in the initial temperature.

A table galvanometer G is controlled by a key K, H being merely a high resistance to protect G at the commencement of the test.

With D on zero, and S on the stud nearest to the air temperature, the supply is switched on and C adjusted to give zero reading on G. As the resistance of F increases due to rise of temperature, resistance is inserted at D to bring G back to zero.

$$\text{Then} \qquad \frac{R_1}{E+S} = \frac{B}{C} = \frac{R_2}{E+S+D}$$

$$\therefore \frac{R_2 - R_1}{R_1} = \frac{D}{E+S}$$

$$\text{But} \qquad \theta_2 - \theta_1 = (234 \cdot 5 + \theta_1)\frac{R_2 - R_1}{R_1}$$

$$= (234 \cdot 5 + \theta_1)\frac{D}{E+S}$$

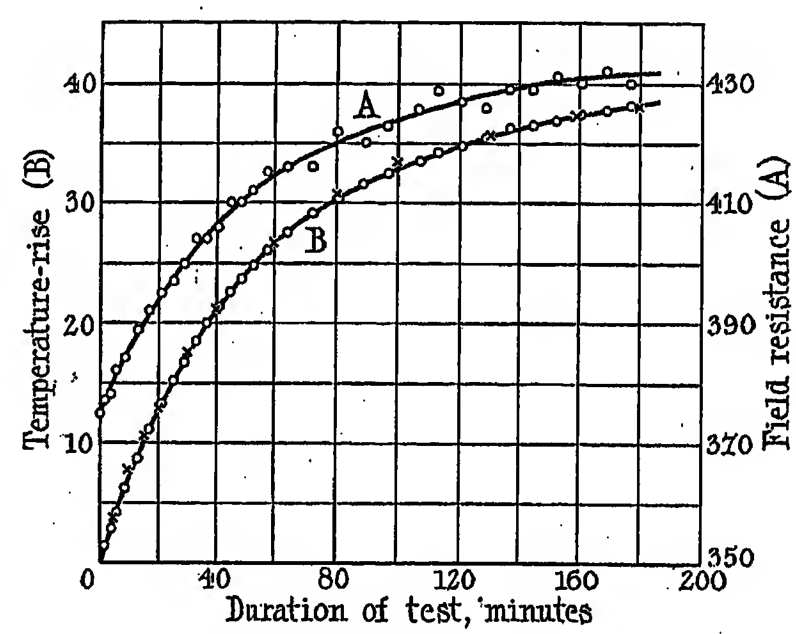

FIG. 12.

When $\theta_1 = 10°$ C., $S = 0$ (10° C. being the minimum air temperature allowed for); and if $\theta_2 - \theta_1 = 10°$ C. we have

$$D = \frac{3\,000 \times 10}{244 \cdot 5} = 122 \cdot 8 \text{ ohms}$$

Hence the resistance per degree C. = 12·28 ohms.

The resistances for dials D have been based on this figure.

In order that S may compensate for the different air temperatures at the commencement of the heating tests, we must have

$$\frac{234 \cdot 5 + \theta_1}{E+S} = \frac{244 \cdot 5}{E}$$

$$\therefore S = \frac{(\theta_1 - 10)E}{244 \cdot 5}$$

Since the dial of S has been arranged for steps of 2 degrees C., the resistance per step = 2 × 3 000/244·5 = 24·56 ohms.

Any variation in the air temperature during a test may be allowed for by moving S to the new air temperature or by correcting the temperature-rise indicated by D.

When the above method was first tried, an ordinary resistance box was used for D, the temperature-rise being calculated from the expression

$$\theta_2 - \theta_1 = \frac{(234 \cdot 5 + \theta_1)}{3\ 000} \times \text{resistance of D}$$

and the results were compared with those calculated from the volt-ammeter readings. Curve A in Fig. 12 shows how difficult it is to obtain consistent values of resistance, although the readings in this test were taken very carefully; the supply voltage, however, was fluctuating quite appreciably. The points marked with a cross on curve B were calculated from the curve drawn through the mean of the resistance points, whilst those indicated by a circle were calculated from the readings obtained by the bridge method just described. Had the temperature-rise been calculated from the actual resistances as measured by the volt-ammeter method, the results would have been much less consistent than the values of the resistance plotted in curve A.

outside thermo-junction (inserted under the outer layer of the coil) have been plotted against armature currents in Fig. 13, and the curves show clearly that the greater

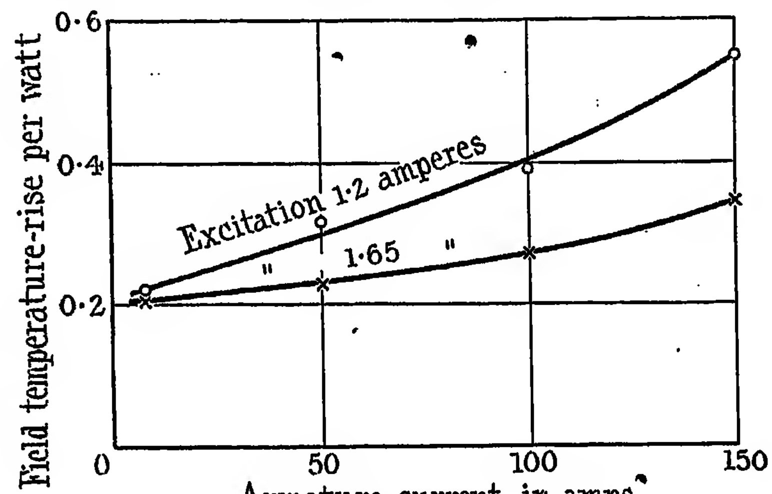

Fig. 13.

cooling effect of the higher speed is much more than counterbalanced by the heating effect of the armature losses, especially at low excitations. Since no data were given concerning the losses, it was not possible to proceed further with the analysis of these results.

Table 9.

Number of test	Peripheral speed	Field current	Armature current	Temperature of outside junction after 3 hours	Corresponding air temperature	Temperature-rise	Field watts	Temperature-rise per watt
	m/sec.	amps.	amps.	°C.	°C.	deg. C.		deg. C.
1	23·56	1·2	8	24·9	18·6	6·3	28·82	0·218
2	17·9	1·65	8	29·9	18·5	11·4	55·14	0·2065
4	23·56	1·2	50	30·5	21·2	9·3	29·43	0·316
5	17·9	1·65	50	34·0	21·0	13·0	56·87	0·2285
7	23·4	1·2	100	31·8	20·2	11·6	29·6	0·392
8	17·9	1·65	100	37·2	21·4	15·8	58·2	0·2715
9	22·9	1·2	150	33·4	17·1	16·3	29·8	0·547
10	17·9	1·65	150	37·1	17·1	20·0	58·2	0·344

It will now be realized that this bridge method enables the temperature-rise of the field to be determined while the machine is running, with a far greater degree of reliability than the usual method, and that its readings are not affected by a fluctuating supply voltage.

8. Heating Tests on Field Coils of Nine Different Machines.

In a paper on "Distribution and Rise of Temperature in Field Coils," * it was submitted that the higher the peripheral speed of the armature the greater the temperature-rise of the field. Such a conclusion was almost obviously wrong. Unfortunately, many of the figures given in Table 2 of the above paper do not agree with the curves, and Table 9 has accordingly been compiled from the data available.

The values of the temperature-rise per watt for the

* *Journal I.E.E.*, 1915, vol. 53, p. 526.

The results of further investigations on field coils by Maclean and Mackellar appeared in the *Electrician* (1917, vol. 79, pp. 465 and 500), the principal conclusions being :—

(*a*) The temperature-rise is given by

$$\theta = \frac{\theta_s}{1 + bv^n}$$

where θ_s = temperature-rise with armature stationary.

When $\theta_s = 29 \cdot 7$ for the machine tested, $b = 0 \cdot 451$ and $n = 0 \cdot 58$, and when $\theta_s = 14 \cdot 8$ for the machine tested, $b = 0 \cdot 644$ and $n = 0 \cdot 39$.

(*b*) The heating coefficient $K (= \theta A/W)$ increases a little with armature current, the effect being more pronounced with low field currents.

(*c*) The ratio (maximum temperature) : (mean temperature) is practically independent of the speed and of the armature current, whilst the ratio (mean tem-

perature) : (surface temperature) is independent of armature current for a given speed, but rises rapidly as the velocity is increased from standstill.

loss upon the field temperature was not realized, and consequently no record was made of the armature temperature. The machines were run on no load in

TABLE 10.

(1) Machine	(2) Peripheral speed	(3) Field current	(4) Temperature-rise by resistance	(5) After a period of	(6) Field watts per dm²	(7) Temperature-rise per watt per dm²	(8) Armature watts/dm²	(9) l	(10) m	(11) n	(12) $\frac{m}{n}$	(13) $\frac{l(1 + mW_a/s_a)}{1 + nv}$	At end of test: Temperature-rise by resistance	At end of test: Temperature-rise by thermometer	At end of test: $\frac{\text{Temp.-rise by resis.}}{\text{Temp.-rise by therm.}}$
	m/sec.	amp.	deg. C.	hours									deg. C.	deg. C.	
C	0	0·45	22·8	3	6·07	3·75	0	3·6	0·035	0·02	1·75	3·6	—	—	—
C	12·4	0·45	26·3	3	6·14	4·28	12·3	3·6	0·035	0·02	1·75	4·12	—	—	—
C	12·4	0·45	22·0	3	6·04	3·64	8·26	3·6	0·035	0·02	1·75	3·72	—	—	—
C	15·8	0·45	22·3	3	6·04	3·69	10·4	3·6	0·035	0·02	1·75	3·74	—	—	—
D	0	1·1	71·1	3	18·7	3·8	0	4·0	0·035	0·07	0·5	4·0	—	—	—
D	3·5	1·1	65·6	3	18·4	3·56	2·21	4·0	0·035	0·07	0·5	3·46	70·2	32·7	2·14
D	7·2	1·1	60·8	3	17·95	3·38	6·47	4·0	0·035	0·07	0·5	3·26	—	—	—
D	11·5	1·1	58·2	3	17·9	3·25	13·2	4·0	0·035	0·07	0·5	3·24	—	—	—
E	8	0·7	18·7	3	7·95	2·35	6·52	3·3	0·025	0·07	0·357	2·46	—	—	—
E	8	0·7	20·0	3	8·0	2·5	13·7	3·3	0·025	0·07	0·357	2·84	—	—	—
E	16	0·7	17·8	3	7·95	2·24	14·4	3·3	0·025	0·07	0·357	2·12	—	—	—
E	16	0·7	20·6	3	8·01	2·57	27·5	3·3	0·025	0·07	0·357	2·62	—	—	—
E	24	0·7	17·2	3	7·91	2·175	26·1	3·3	0·025	0·07	0·357	2·04	—	—	—
E	24	0·7	20·6	3	8·0	2·58	38·1	3·3	0·025	0·07	0·357	2·41	—	—	—
F	0	0·565	67·8	6	9·53	7·11	0	7·1	0·025	0·065	0·385	7·1	67·2	49·5	1·36
F	2·17	0·565	61·0	6	9·37	6·51	1·73	7·1	0·025	0·065	0·385	6·49	61·6	46·3	1·33
F	5·42	0·565	55·0	6	9·18	6·0	5·84	7·1	0·025	0·065	0·385	6·01	55·7	40·0	1·39
F	11·0	0·565	52·8	6	9·22	5·73	15·5	7·1	0·025	0·065	0·385	5·76	53·6	33·5	1·6
F	0	0·5	54·3	6	7·29	7·45	0	7·45	0·026	0·05	0·52	7·45	54·5	37·4	1·46
F	2·88	0·5	51·2	6	7·33	6·99	2·24	7·45	0·026	0·05	0·52	6·89	51·8	33·0	1·57
F	5·7	0·5	47·5	6	7·17	6·62	5·5	7·45	0·026	0·05	0·52	6·63	47·5	30·0	1·58
F	11·62	0·5	47·0	6	7·11	6·61	15·5	7·45	0·026	0·05	0·52	6·61	—	—	—
F	0	0·4	37·3	6	4·38	8·51	0	8·5	0·021	0·03	0·70	8·5	—	—	—
F	3·38	0·4	35·5	6	4·4	8·06	2·27	8·5	0·021	0·03	0·70	8·08	35·5	23·0	1·54
F	6·48	0·4	35·0	6	4·36	8·02	5·85	8·5	0·021	0·03	0·70	8·0	35·0	23·3	1·50
F	9·69	0·4	35·5	6	4·41	8·05	10·0	8·5	0·021	0·03	0·70	7·99	35·6	20·5	1·73
F	13·37	0·4	35·5	6	4·4	8·06	16·35	8·5	0·021	0·03	0·70	8·15	35·5	22·8	1·56
G	0	0·8	84·6	6	11·97	7·07	0	7·1	0·0145	0·055	0·264	7·1	85·0	53·5	1·59
G	3·7	0·8	69·0	6	11·33	6·08	2·52	7·1	0·0145	0·055	0·264	6·1	69·0	40·2	1·72
G	7·33	0·8	65·0	6	11·43	5·68	7·6	7·1	0·0145	0·055	0·264	5·62	65·3	37·9	1·72
G	15·0	0·8	57·3	6	11·12	5·14	22·6	7·1	0·0145	0·055	0·264	5·16	57·3	34·3	1·67
G	0	0·7	67·0	6	8·58	7·81	0	7·8	0·030	0·10	0·30	7·8	—	—	—
G	3·81	0·7	47·5	6	8·03	5·92	1·31	7·8	0·030	0·10	0·30	5·87	47·5	32·1	1·48
G	7·72	0·7	41·5	6	7·94	5·22	6·24	7·8	0·030	0·10	0·30	5·22	41·5	27·5	1·51
G	15·8	0·7	38·3	6	7·84	4·88	20·5	7·8	0·030	0·10	0·30	4·88	38·3	25·9	1·48
G	0	0·5	36·3	6	3·88	9·35	0	8·7	0·020	0·047	0·425	8·7	—	—	—
G	0	0·5	31·1	6	3·88	8·01	0	8·7	0·020	0·047	0·425	8·7	31·2	19·5	1·60
G	4·83	0·5	27·6	6	3·82	7·22	2·4	8·7	0·020	0·047	0·425	7·42	27·6	16·5	1·67
G	4·97	0·5	28·2	6	3·82	7·38	2·42	8·7	0·020	0·047	0·425	7·37	28·2	17·0	1·66
G	9·65	0·5	26·6	6	3·8	7·0	6·8	8·7	0·020	0·047	0·425	6·8	26·6	15·5	1·71
G	19·3	0·5	25·3	6	3·78	6·69	25·1	8·7	0·020	0·047	0·425	6·85	25·4	15·8	1·61

It was with the object of investigating this problem more completely and of comparing the results for different types of machines that the following tests were conducted. At the time, the effect of the armature loss upon the field temperature was not realized, and consequently no record was made of the armature temperature. The machines were run on no load in practically all the tests; and as the iron losses for the machines had been determined very carefully it has been found possible to take into account the effect of armature loss.

TABLE 10—*continued.*

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	At end of test		
Machine	Peripheral speed	Field current	Temperature-rise by resistance	After a period of	Field watts per dm²	Temperature-rise per watt per dm²	Armature watts/dm²	l	m	n	$\frac{m}{n}$	$\frac{l(1+mW_a/\Delta a)}{1+nv}$	Temperature-rise by resistance	Temperature-rise by thermometer	Temp.-rise by resis. / Temp.-rise by therm.
	m/sec.	amp.	deg. C.	hours									deg. C.	deg. C.	
	0	1·0	94·2	6	15·42	6·1	0	6·1	0·027	0·05	0·54	6·1	94·2	54·5	1·73
	3·04	1·0	83·0	6	15·08	5·5	1·45	6·1	0·027	0·05	0·54	5·5	81·0	42·5	1·905
	6·88	1·0	75·5	6	14·85	5·08	4·26	6·1	0·027	0·05	0·54	5·06	76·1	38·5	1·98
	14·1	1·0	68·4	6	14·37	4·76	12·52	6·1	0·027	0·05	0·54	4·77	68·6	39·5	1·74
	0	0·85	72·0	6	10·83	6·65	0	6·65	0·030	0·05	0·6	6·65	74·0	38·0	1·95
	3·78	0·85	61·3	6	10·48	5·85	1·705	6·65	0·030	0·05	0·6	5·88	62·0	33·0	1·88
	7·28	0·85	58·4	6	10·3	5·66	4·13	6·65	0·030	0·05	0·6	5·48	—	—	—
H	11·05	0·85	54·0	6	10·14	5·32	7·65	6·65	0·030	0·05	0·6	5·28	54·0	29·0	1·86
	15·04	0·85	52·5	6	10·1	5·2	12·35	6·65	0·030	0·05	0·6	5·21	53·6	27·2	1·97
	0	0·6	34·2	6	4·9	6·98	0	7·0	0·050	0·05	1·0	7·0	34·2	21·2	1·61
	1·9	0·6	31·0	6	4·89	6·34	0·545	7·0	0·050	0·05	1·0	6·56	31·3	18·0	1·74
	4·16	0·6	30·2	6	4·89	6·17	1·4	7·0	0·050	0·05	1·0	6·21	30·6	18·0	1·70
	8·32	0·6	28·1	6	4·78	5·88	3·58	7·0	0·050	0·05	1·0	5·83	28·1	15·5	1·81
	12·57	0·6	29·2	6	4·85	6·02	6·61	7·0	0·050	0·05	1·0	5·72	29·2	15·5	1·88
	17·05	0·6	27·6	6	4·78	5·77	10·65	7·0	0·050	0·05	1·0	5·80	27·6	15·5	1·78
	0	1·0	83·7	6	14·15	5·91	0	5·9	0·034	0·06	0·566	5·9	83·7	49·0	1·71
	3·04	1·0	73·0	6	13·83	5·27	1·56	5·9	0·034	0·06	0·566	5·25	71·0	40·3	1·76
	6·88	1·0	64·7	6	13·51	4·78	4·68	5·9	0·034	0·06	0·566	4·83	65·0	35·3	1·84
	14·1	1·0	62·5	6	13·25	4·71	13·8	5·9	0·034	0·06	0·566	4·68	62·5	32·5	1·92
	0	0·85	65·5	6	9·97	6·57	0	6·6	0·029	0·055	0·528	6·6	67·0	36·3	1·85
	3·78	0·85	55·0	6	9·62	5·72	1·91	6·6	0·029	0·055	0·528	5·76	56·0	29·0	1·93
	7·28	0·85	52·5	6	9·48	5·54	4·62	6·6	0·029	0·055	0·528	5·36	—	—	—
I	11·05	0·85	48·2	6	9·41	5·12	8·58	6·6	0·029	0·055	0·528	5·14	48·2	24·5	1·97
	15·04	0·85	47·5	6	9·38	5·06	13·95	6·6	0·029	0·055	0·528	5·08	47·5	22·7	2·09
	0	0·6	32·4	6	4·55	7·12	0	7·1	0·056	0·055	1·02	7·1	32·4	20·5	1·58
	1·9	0·6	29·1	6	4·53	6·43	0·626	7·1	0·056	0·055	1·02	6·65	29·4	18·0	1·63
	4·16	0·6	28·5	6	4·53	6·29	1·62	7·1	0·056	0·055	1·02	6·31	28·8	16·0	1·80
	8·32	0·6	27·5	6	4·46	6·19	4·15	7·1	0·056	0·055	1·02	6·01	27·6	14·5	1·90
	12·57	0·6	27·4	6	4·51	6·08	7·64	7·1	0·056	0·055	1·02	5·99	27·4	12·5	2·19
	17·05	0·6	27·1	6	4·46	6·08	12·35	7·1	0·056	0·055	1·02	6·2	27·1	15·5	1·75
	0	0·93	72·5	6	13·1	5·53	0	5·5	0·0205	0·06	0·342	5·5	75·7	52·1	1·45
	6·5	0·93	52·6	6	12·11	4·34	4·86	5·5	0·0205	0·06	0·342	4·35	52·8	34·0	1·55
	16·9	0·93	45·8	6	12·02	3·805	19·1	5·5	0·0205	0·06	0·342	3·80	45·8	27·5	1·66
	22·5	0·93	46·0	6	12·02	3·82	30·2	5·5	0·0205	0·06	0·342	3·79	—	—	—
	33·6	0·93	47·2	6	12·1	3·9	56·9	5·5	0·0205	0·06	0·342	3·95	47·2	31·5	1·50
J	0	0·625	40·1	6	5·19	7·72	0	7·7	0·041	0·06	0·684	7·7	40·1	22·2	1·8
	4·4	0·625	33·0	6	5·10	6·47	2·12	7·7	0·041	0·06	0·684	6·61	33·1	19·0	1·74
	9·95	0·625	31·1	6	5·04	6·16	6·1	7·7	0·041	0·06	0·684	6·02	31·1	15·0	2·07
	19·4	0·625	31·0	6	5·09	6·08	16·3	7·7	0·041	0·06	0·684	5·92	31·0	17·5	1·77
	28·7	0·625	33·6	6	5·14	6·53	30·5	7·7	0·041	0·06	0·684	6·38	33·6	16·0	2·1
	29·0	0·625	31·6	6	5·12	6·17	31·0	7·7	0·041	0·06	0·684	6·38	31·6	17·0	1·86
	0	2·05	83·1	6	11·55	7·2	0	7·2	0·0148	0·05	0·296	7·2	83·1	42·5	1·95
	6·5	2·05	61·4	6	10·92	5·51	5·02	7·2	0·0148	0·05	0·296	5·84	61·4	29·5	2·08
	16·9	2·05	55·5	6	10·68	5·2	21·9	7·2	0·0148	0·05	0·296	5·17	55·5	25·5	2·18
	22·5	2·05	54·0	6	10·59	5·1	34·6	7·2	0·0148	0·05	0·296	5·13	—	—	—
	33·6	2·05	56·8	6	10·75	5·27	64·9	7·2	0·0148	0·05	0·296	5·26	56·8	25·0	2·27
K	0	1·55	57·0	6	6·08	9·37	0	9·3	0·025	0·05	0·5	9·3	56·3	24·0	2·34
	4·4	1·55	48·2	6	5·96	8·09	2·39	9·3	0·025	0·05	0·5	8·09	48·2	19·0	2·54
	9·95	1·55	43·0	6	5·85	7·35	7·51	9·3	0·025	0·05	0·5	7·39	—	—	—
	19·4	1·55	43·0	6	5·81	7·4	21·7	9·3	0·025	0·05	0·5	7·3	43·0	18·0	2·39
	29·0	1·55	44·0	6	5·92	7·44	41·2	9·3	0·025	0·05	0·5	7·7	44·0	17·0	2·59

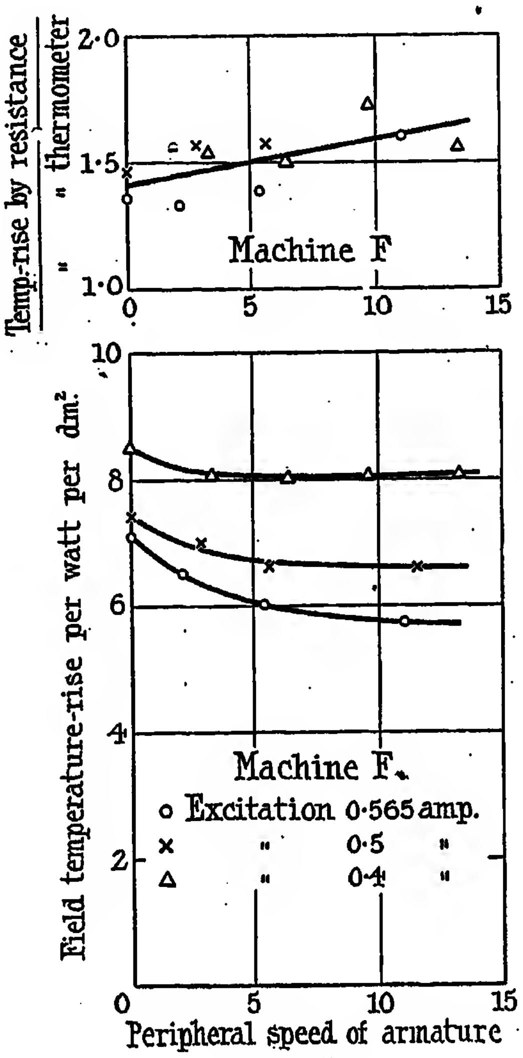

FIG. 14.

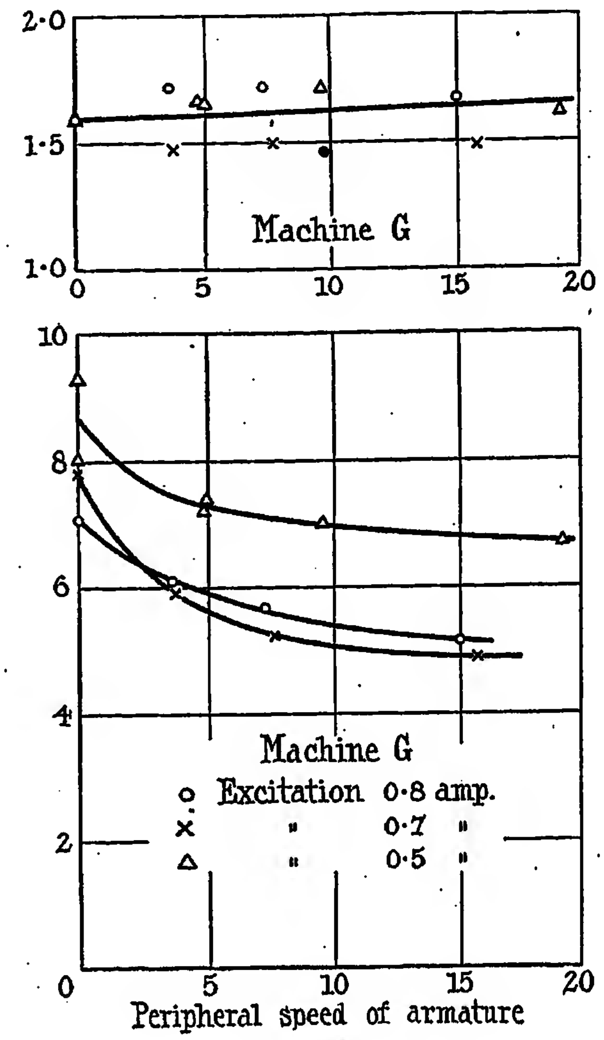

FIG. 15.

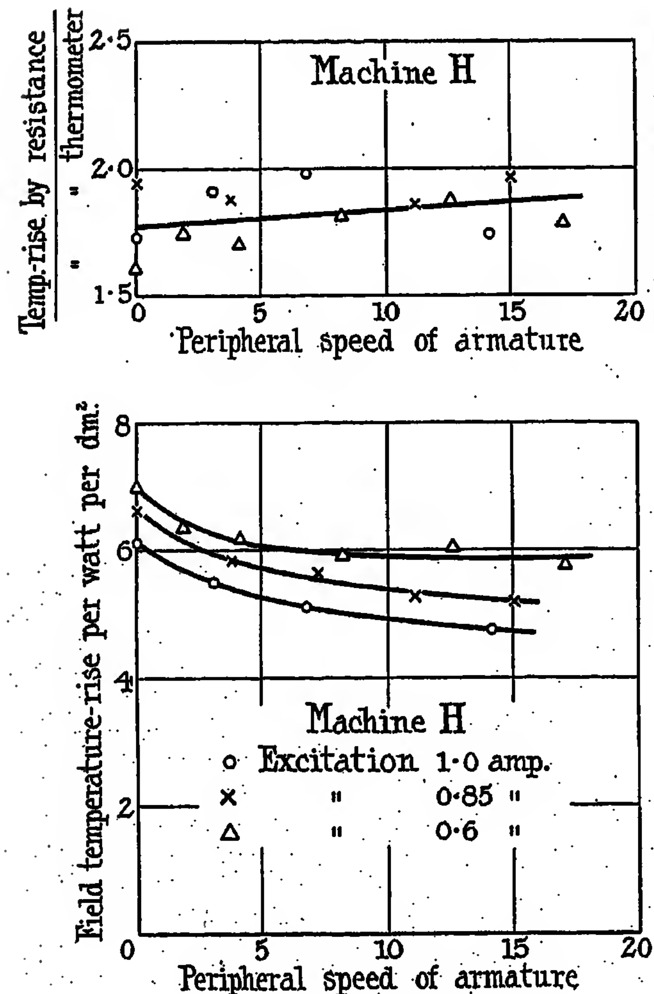

FIG. 16.

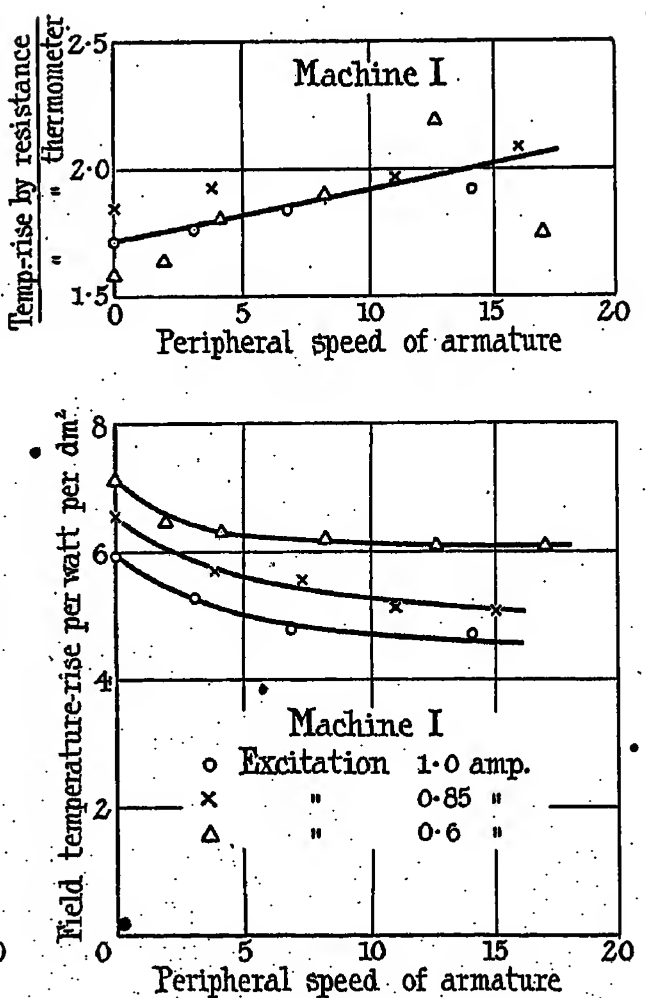

FIG. 17.

The temperature-rise of the field windings for all the machines except C, D and E was determined by the volt-ammeter method, but for these three machines the bridge method described on page 640 was employed. In most cases the final temperature-rise of the field coils on one of the upper poles was measured by a thermometer, the latter being placed on the surface facing another main pole or commutating pole and protected by cotton waste. All the thermometer readings were taken immediately after stopping the machines.

Table 10 gives the results obtained on these tests, and the curves in Figs. 14 to 19 show how the temperature-rise per watt per dm² varies with the speed for machines F to K. These curves were thought to be of the form represented by

$$\frac{\theta_f A_f}{W_f} = \frac{k}{1 + a\sqrt{v}} \text{ (where } k \text{ and } a \text{ are constants),}$$

but a closer inspection of the curves—especially those for machines J and K—indicated that the effect of the armature loss must not be neglected, and that the temperature-rise of the field is more correctly represented by

$$\frac{\theta_f A_f}{W_f} = \frac{l(1 + mW_a/A_a)}{1 + nv}$$

where l, m and n are constants for a given machine, v is the peripheral speed of armature in m/sec., and W_a/A_a is the armature loss in watts per dm² of armature surface.

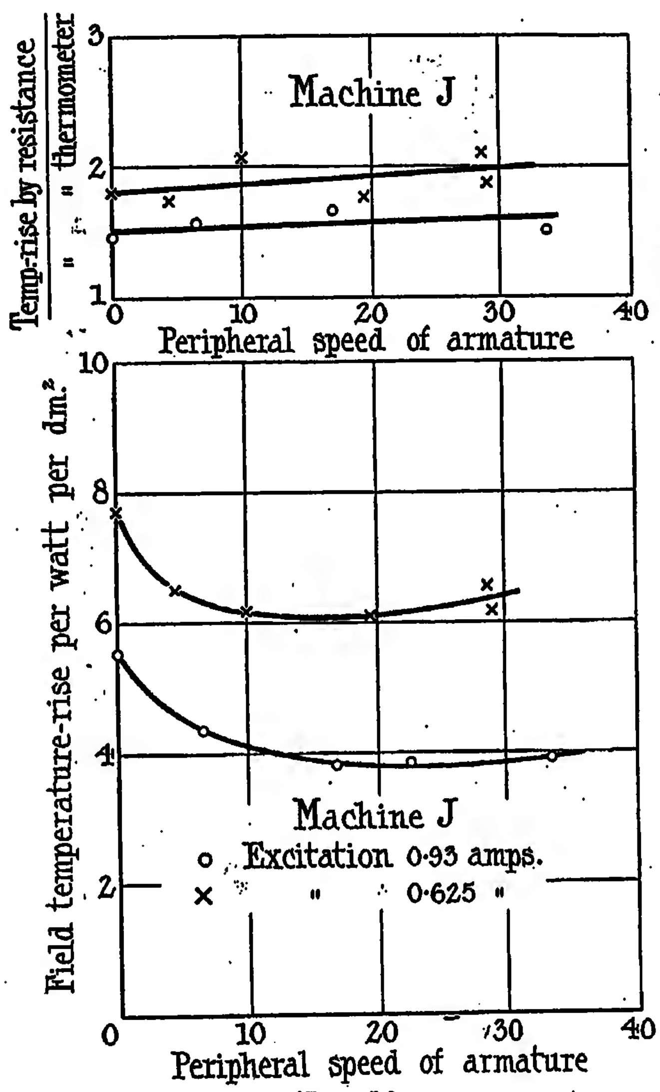

Fig. 18.

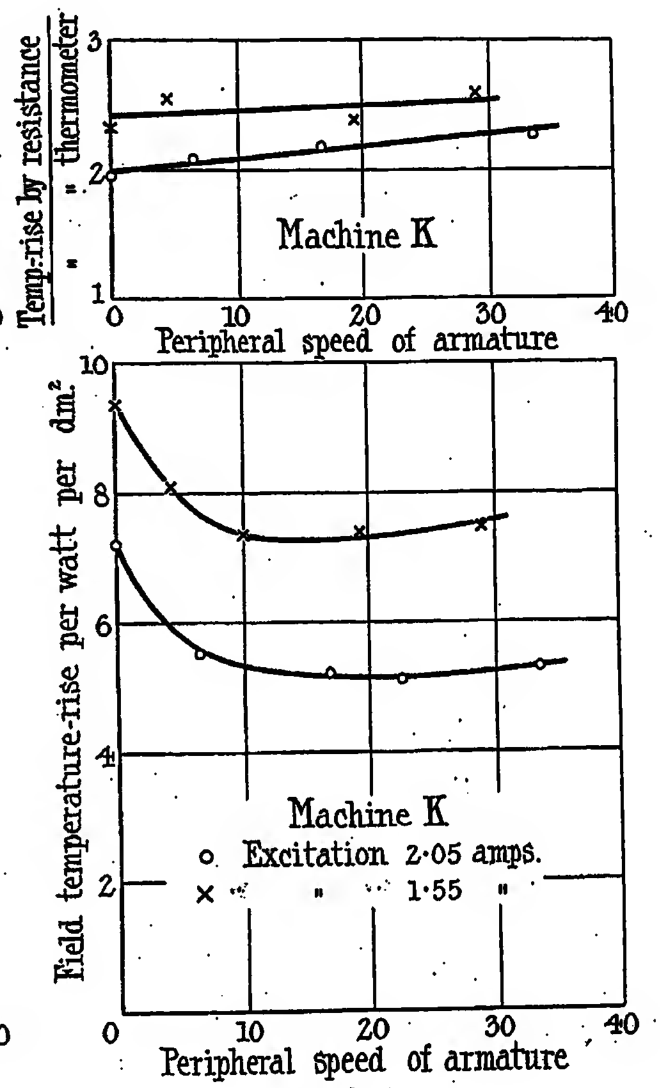

Fig. 19.

The values of l, m and n for the various machines are given in Table 10; and col. (13) shows how closely the values calculated from this expression agree with the values in col. (7) deduced from the test-results.

In order to show how the value of l varies for different machines and for different temperature-rises of a given machine, the curves in Fig. 20 have been drawn. On page 637 it was shown that the temperature-rise per watt per dm² for stationary coils could be expressed in the form

$$\frac{\theta A}{W} = \frac{c}{1 + a\theta}.$$

Applying this expression to the curves in Fig. 20 we have the results given in Table 11.

Table 11.

Machine	c	a
F	11·0	0·00855
G	10·4	0·00546
H	7·76	0·00263
I	8·23	0·00438
J	15·15	0·0242
K	25·5	0·0306

The average value of a for protected-type machines may be taken as 0·005, which is the same as that given

on page 637. For the open-type machines, J and K, the values of a appear to be unduly high, and the values of c are in consequence also very high. The comparatively high values of l for machine K are probably due to the fact that this machine was fitted with a compensating winding which shielded the shunt winding to some extent.

The values of m and n in Table 11 depend upon the

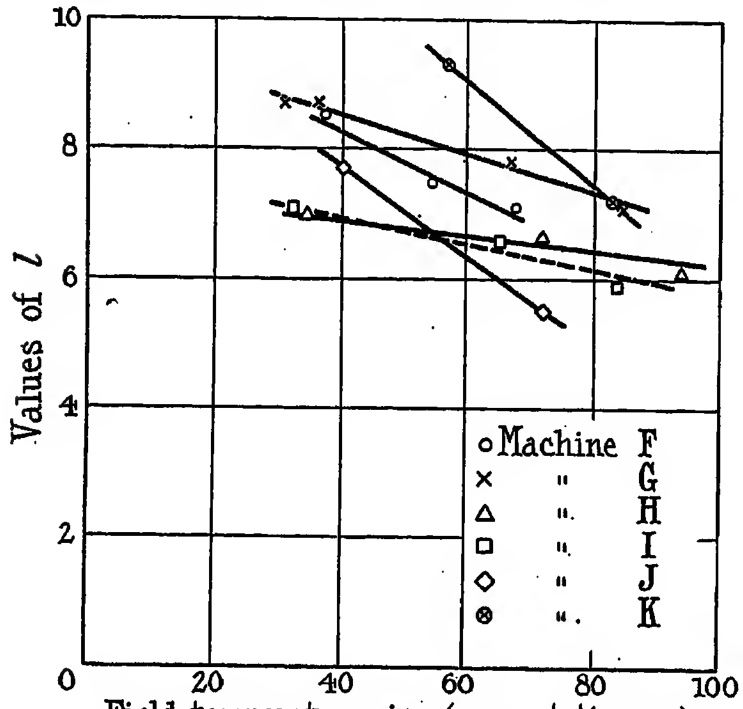

FIG. 20.

arrangement and ventilation of the armature winding, the presence of a fan on the armature, the proximity of the field winding to the armature, the relative temperatures of the field and armature windings, etc. In order to trace the variation of m and n for the different conditions, the ratio m/n has been calculated in Table 10

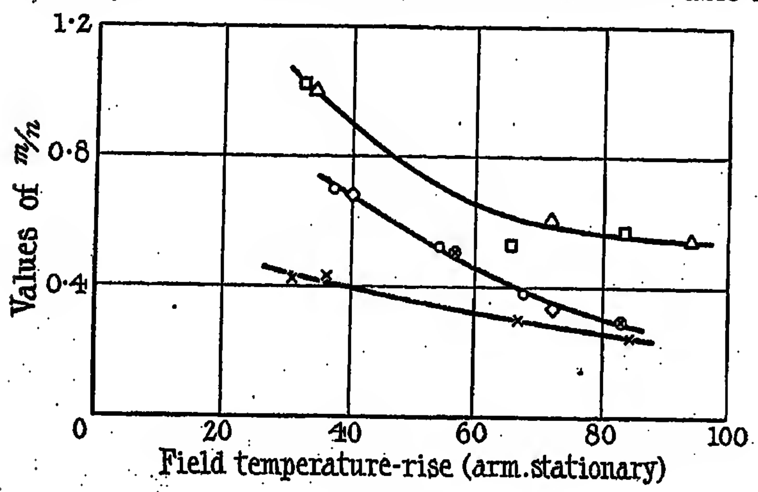

FIG. 21.

and plotted against field temperature-rise in Fig. 21. From these curves it is seen that:—

(a) The lower the temperature-rise of the field, the greater the effect of armature loss in comparison with that of speed.

(b) The effect of fitting an armature with a fan as in machine G is to reduce the ratio m/n, i.e. to make the speed relatively more important than the armature loss. Also, with the open-type machines J and K the ratio is much smaller than for the protected-type machines H and I by the same makers.

(c) The influence of the proximity of the field coils to the armature is very evident by comparing the ratios for m/n given in Table 10 for machines C and D. Each of these machines has a series winding of approximately the same size as the shunt, but in machine D the shunt winding is the nearer to the armature, whilst in the other machine the series winding is the nearer.

(d) The temperature-rise per watt per dm^2 of the field winding of protected-type machines is given approximately by

$$\frac{\theta_f A_f}{W_f} = \frac{7 \cdot 5(1 + 0 \cdot 03 W_a / A_a)}{1 + 0 \cdot 05 v}$$

9. COMPARISON OF TEMPERATURE-RISES BY RESISTANCE AND BY THERMOMETER.

The ratio of temperature-rise by resistance to that by thermometer has been calculated wherever possible in Table 10, and has been plotted in Figs. 14 to 19. There is a certain amount of inconsistency noticeable in some cases, due mainly to the difficulty of taking reliable thermometer readings. The ratio in most cases shows an inclination to increase with increase of speed, probably due to the greater temperature gradient produced in the outer half of the coil by the greater ventilation. The ratio for machine K is decidedly higher than for the other machines, and this may be due to heavier insulation on the field coils owing to the compensating winding being in close proximity. It is not due to an abnormally high temperature gradient in the winding, because it has been shown on page 630 that the effect of the insulating covering on the wire of these coils is much less than in any of the other coils. Also, the coils are shallower than those of machines H, I and J, and all these coils had been thoroughly impregnated (see page 648).

Table 12 has been compiled to show that the ratios obtained above are not abnormally high for coils wound with d.c.c. wire. The data for coils numbered 2A to 8B have been taken from Rayner's paper,* whilst the values for coils R1 to R5 were given by Rayner in the *Electrician*.*

The above figures for the relation between the mean temperature-rise and the temperature-rise measured by thermometer are sufficient to demonstrate the unreliability of the thermometer reading as an indication of either the mean or the maximum temperature-rise of a field winding, though the thermometer method alone is recommended by the British Engineering Standards Association (B.S.S. No. 168). The results given above also indicate that unless the temperature-rise by resistance for taped coils is allowed to be at least 70 per cent greater than that by thermometer, the resistance method is handicapped in comparison with the thermometer method.

The author desires to express his thanks to Prof. F. G. Baily for permission to carry out the tests on coil A and on machines F to K at the Heriot-Watt College, Edinburgh. The tests on coil B and on machines C, D and E were performed at the Brighton Technical College, and the author's thanks are due to Mr. H. A. Ashdown, B.Sc.(Eng.), who did most of the observational work.

* *Loc. cit.*

TABLE 12.

Coil	Temp.-rise by resistance	Temp.-rise by thermometer	Rise by resis. / Rise by therm.	Conditions of test	Remarks
	deg. C.	deg. C.			
A (0·6A)	79·9	51·5	1·55	Suspended in air	d.c.c.
A (0·56A)	69·3	43·5	1·59	Suspended in air	d.c.c.
2A	84	34	2·47	Running loaded	d.c.c.; thoroughly impregnated and covered with 2 layers linen tape, ½ lap
2B	75	32	2·34	Running light	
4B	62·7	45	1·4	Running loaded	s.c.c.; no tape
5	40·5	22	1·84	Running loaded	d.c.c.; no tape
7A	66·5	36	1·85	Running loaded	d.c.c.; shallow series winding over shunt
7B	50	29	1·72	Standing	
7C	89·5	49	1·83	Standing	
8A	60	5	12	Running loaded	d.c.c.; covering ½ in. thick of insulation and string
8B	118	31	3·81	Running loaded	Enamelled wire
R1	29	23·5	1·23	Running loaded	Enamel and dipped in "Voltalac"
R2	29	20·3	1·43	Running loaded	d.c.c.
R3	34	25·2	1·35	Running loaded	d.c.c., and dipped in "Voltalac"
R4	36·4	27·5	1·323	Running loaded	d.c.c.; coil finished with layer of tape
R5	51·1	27·4	1·865	Running loaded	

APPENDIX.

PRINCIPAL DATA OF THE COILS AND MACHINES ON WHICH THE FOREGOING EXPERIMENTS HAVE BEEN PERFORMED.

	A	B	C	D	E	F	G	H	I	J	K
Type *	—	—	P	P	P	P	P	P	P	O	O
Armature.											
Diameter (cm)	—	—	21·6	19·06	20·35	25	29·5	30·5	30·5	33	33
Core length (cm)	—	—	15·25	12·71	10·2	14	14	15·25	15·25	16·5	16·5
Overall length of winding (cm)	—	—	31·3	26·0	24·0	32·5	35·4	37·5	37·5	39·5	39·5
Cylindrical area of winding (dm^2)	—	—	21·2	15·6	15·33	25·5	32·8	35·9	35·9	41	41
Shunt Winding.											
Number of turns	3 800	2 000	3 300	1 600	2 400	3 800	3 780	3 654	3 654	4 018	1 188
Diameter of wire (mm)	0·545	0·0144	0·61	0·711	0·635	0·584	0·635	0·762	0·762	0·762	1·142
Covering on wire	d.c.c.	d.c.c.	s.c.c.	d.c.c.	s.c.c.	d.c.c.	s.c.c.	d.c.c.	d.c.c.	d.c.c.	d.c.c.
Area of wire (mm^2)	0·232	0·657	0·292	0·397	0·3167	0·268	0·3167	0·456	0·456	0·456	1·025
Length of coil (cm)	9·0	6·8	4·8	4·0	7·4	9·0	10	9·5	9·5	10·5	7·0
Depth of coil (cm)	4·5	4·5	4·7	5·0	2·5	4·5	3	4·8	5·2	4·9	4·2
Total cylindrical area of coils (dm^2)	6·4	2·78	13·4	12·5	13·2	25·6	32	27·2	28·9	31·6	28·56
Shape of coil †	R	C	R	R	C	R	R	C	C	C	R
Total external surface of machine (dm^2)	—	—	—	—	108	—	—	—	—	—	—
Total surface of coil (dm^2)	16·7	—	—	—	—	—	—	—	—	—	—
Volume of coil (cm^3)	2 540	817	—	—	—	—	—	—	—	—	—

* P and O signify "protected type" and "open type" respectively.
† R and C signify "rectangular" and "circular" respectively.

ADDITIONAL PARTICULARS.

(A) Coil wound on a press-spahn former and taped half-lap. Five thermo-junctions were inserted in the positions described on page 632.

(B) Coil wound on a brass former with leatheroid insulation and varnished on the outside. Five thermo-junctions also inserted in the coil in the positions described on page 638.

(C) 5 kW dynamo. Machine has a series field winding of nearly the same size as the shunt, the series winding being side by side with the shunt but nearer the armature.

(D) 3·5 kW dynamo. This machine also has a series field winding of approximately the same dimensions as the shunt, but the series winding in this case is the further away from the armature.

(E) 3·5 kVA three-phase alternator with revolving armature.

(F) 10 b.h.p. shunt interpolar motor. The field coils are impregnated.

(G) 15 b.h.p. shunt interpolar protected-type motor, fitted with a fan at the back of the armature. The field coils are wound with untreated wire, dried in a vacuum and impregnated, after which they are taped and varnished.

(H) 20 b.h.p. shunt interpolar motor direct coupled to a non-interpolar generator I. The field windings are similar except that machine I has a series winding of 32 turns of 3·43 × 3·43 mm wire in two layers on top of the shunt. The makers state that "the field coils are all impregnated *in vacuo*, being placed in a vacuum chamber for 12 hours at a temperature of 180° F. They are then impregnated under a pressure of 35–40 lb. with standard black solid compound, the coils then being completely covered with flexible mica cloth and waterproof tape."

(J) 60 b.h.p. shunt interpolar motor direct coupled to a shunt interpolar generator K. The field coils of both machines were subjected to the same treatment as were H and I. Machine K is fitted with a compensating winding.

DISCUSSION ON "THE CHARACTERISTICS OF A D.C. SERIES MACHINE SELF-EXCITED BY RECTIFIED CURRENT FOR PURPOSES OF REGENERATIVE CONTROL." *

SCOTTISH CENTRE, AT DUNDEE, 25 APRIL, 1924.

Mr. D. H. Bishop: The paper describes a very ingenious method by which a series motor can be transformed at a moment's notice into what is virtually a shunt motor. It has occurred to me that a certain amount of saving in energy consumption would be possible, in connection with tramway work, if, having started up the car by means of motors connected as series motors, they could then be converted into shunt motors. If it is required to run at a constant speed, that could no doubt be done without wasting power in resistance. This would mean that some form of speed regulation would be required, and that is also necessary if the full benefit of regenerative control is to be obtained. I should like to ask the author whether he would put a rheostat in the primary circuit of the transformer or whether he would try to alter the ratio of the latter. Table 1 shows some results obtained with the brushes in various positions. Is there any practical objection to keeping the brushes in, say, position 5, independent of the direction of rotation? I fancy that the difference of potential between the two segments of the rectifier is only a matter of 10 volts at the maximum, and is therefore not likely to be a source of trouble on account of short-circuits across the insulation between segments. There is a very low voltage at the rectifier, and the author mentions that he had to use a considerable pressure on the brushes. I take it that the reason is that the rectifier would not otherwise excite. Does this mean that carbon brushes cannot be used? The use of metal brushes on slip-rings is to be avoided if possible.

Dr. S. Parker Smith: The author has worked out a very ingenious method and has proved the method to be a success. As he would tell us himself, this is by no means the first device that has been developed for regenerating energy from traction motors. Perhaps it would be well to examine very briefly the position of the matter as it stands at the present day, rather than to discuss technical details which the author has already put clearly before us. We are stopping electric trains and tramcars innumerable times a day, and why is it that we waste all the energy? Why is it also that regeneration in regard to main-line work is going out of use? It was introduced and it was thought that a great improvement in efficiency would result. What do we find? In many countries where the conditions are specially suitable for the regeneration of energy the regenerative apparatus has been discarded, because the return was not worth the trouble. The French welcomed regeneration with great enthusiasm; the Italians before them did the same, likewise the Swiss. What has happened? Very often when they got the energy they did not know what to do with it, for there was not a train climbing when another was descending. In many cases the complication and cost are scarcely justified with water power, apart from the practical difficulty of securing some use for the energy. In America better results are claimed—but even there the results are not altogether perfect. Regenerative energy can be bought at too dear a price. To prevent wear and tear on the tyres, on the brake shoes and on the rails, a simple alternative is rheostatic braking, and that is what many people are adopting. Coming to the case of the motor coach, which is starting and stopping every mile or so, and where the cost of energy is a large part of the working cost, a strong case can be made out for regeneration, for even a few per cent in the cost is a good reduction. Here, however, restrictions imposed by the limits of space available render the installation of the essential equipment difficult. As soon as a motor is made to regenerate, the machine may be overloaded. In other words, the motors cannot work also as generators without overheating. That is

* Paper by Dr. R. D. Archibald (see page 288).

one great reason why none of these schemes has come into use on the suburban railways. On the tramcars rheostatic braking is used, and the motors could here be made to regenerate; but it is not needed only when a tramcar descends a hill. The great saving would ensue if the energy could be regenerated while the tramcar is being brought to rest. My criticisms are not directed against the device, but are simply intended to point out some of the practical difficulties to be overcome in adopting regenerative methods.

Mr. A. P. Robertson: Regarding the connections for this method of regeneration, it seems to me that there would be a great many contacts on the controller, which would consequently be much more complicated than it is at present. In practical working, would the motor run as a series motor with the rectifier and transformer always in circuit, or would the field switch be opened at starting, which would make it a plain series motor? I take it that, after the motor is up to speed, the rectifier switch is closed and the field built up as a shunt from the armature, and that the end of the series field is then disconnected from the line and put direct on the brushes of the armature. If that is so, this alone will result in a considerable number of extra contacts. Then, again, the brushes are shown in the neutral position, which is not the best place. The best place is a little in advance, and, as the machine has to run in both directions, the position of the brushes requires to be altered according to the direction of the motor. All this has to be done with one handle, and may call for mechanical connections from the controller to the brush gear. On page 234 the current density on brush 5 is given as 47 amperes per sq. in. at full load (17·5 amperes). That figure was taken on a 5 h.p. motor at 400 volts. On a 600-volt circuit and a 40-h.p. motor, the current would be about 40 amperes, and much larger brushes would be required. The brush pressure is given as 14 lb./sq. in. This is rather high; the usual pressure is nearer 5 lb./sq. in. I think that metal brushes will have to be used to get the requisite current density. The difficulty with the metal brush is lubrication, and there are many methods of oiling. So far we have found that the best method is hand lubrication, but that method could not be applied to the brushes of a tramway motor. I had thought that railways would be ideal for regenerative control because of the long gradients, but from Dr. Parker Smith's remarks it appears that, due to the infrequency of running, regenerative control is not so suitable as on tramways. With tramways there is a large amount of town work. Cars in busy streets move for only a short distance at a time and that very slowly, and the regeneration, to be of any use, would require to be effective at a low speed. On the other hand, on long runs where there are gradients some use might be made of it. What is the lowest speed at which regeneration would be effective by this method?

Mr. W. B. Hird: It appears to be largely a question of the complications necessarily added to the equipment in order to obtain a satisfactory regenerative control. It is difficult to believe that the extensive additions to the equipment proposed in the paper are the simplest and easiest solution of the problem. I do not think that a practical tramway engineer would agree to the proposal that he should add slip-rings and an additional set of brush gear to his motors. I have had a considerable experience of another class of motors, namely coal-cutter motors, where there are very severe restrictions on the space available, and I am therefore fully able to realize the difficulties involved and the sacrifice of existing useful properties which would be involved in finding room for slip-rings and an additional set of brush gear. The complications required are not confined to the motor. The switching arrangements also must be added to, and if it became also necessary to make arrangements for shifting the brushes it appears that the advantages to be gained from regenerative control would be more than outweighed by the complications added to the equipment and the sacrifices required to find space for these additions. Mr. Robertson asked how far the speed could be reduced by means of regenerative control. It is obvious from the speed curves given in the paper that the speed could not be brought down to very low limits by this means, and that the chief gains to be derived from the return of energy to the line would be obtained not at stops but when coasting down hills of some length and of a considerable gradient. In this connection I think that the difference between a tramway service and a railway service has not been sufficiently emphasized. On a railway, it would generally be possible to coast down the hills uninterrupted by any traffic stops; in a tramway system, however, even with considerable gradients in the different routes, free coasting is liable to constant traffic interruptions and therefore loses much of its value. Take, for example, the Glasgow system, which has considerable hills. How often would a car be able in a day's work to run down Renfield-street without several traffic stops interfering with the regenerative process? In spite of the advantages of railways over tramways in this respect, Dr. Parker Smith has told us that regenerative control has been abandoned on several railways where it had been originally used, because the gain was not worth the added complications. Although the author's method is very ingenious, I feel that regenerative control has little, if any, future before it, and it is especially doubtful whether a tramway system would ever derive much benefit from this or any other system.

Dr. R. D. Archibald (*in reply*): In reply to Mr. Bishop, the question of whether the speed should be controlled by a rheostat in the primary or by varying the ratio of the transformer depends on whether a fine adjustment or large range of speed is required. I am of the opinion that for many purposes two speeds, obtained by varying the ratio, would be sufficient, but a combination of both methods could be used with advantage if not too complicated. The brush position 5 in Table 1 is the proper running position and gave good results in both directions. I may say that a more accurate method of setting the brushes, which was employed later, indicated that the brush settings given in Table 1 were half a mica-width further back than shown and that the tests were really performed on a setting between 4 and 5. There is, of course, no question of shifting the brushes on reversing the direction of

rotation. The tests in different positions were taken merely to show the effect on the characteristics. There was no danger from short-circuits between the segments, as the voltage was from 5 to 10 volts and the segments were 0·1 in. apart, which is much wider than in an ordinary commutator. Copper brushes were used for 4, 4′, in Fig. 1 as they were handy, but the slight extra drop incurred by using graphite brushes would not have made any appreciable difference. Excitation was easily obtained at normal brush pressure of $1\frac{1}{2}$ to 2 lb. when the commutator ran true. The contact resistance of a carbon brush increases with pressure up to 4 or 5 lb. per sq. in., after which further increase of pressure makes little or no difference. It is therefore essential to use a pressure of not less than about 5 lb. per sq. in. In the tests higher pressures were used, as the commutator developed a slight wobble, and the 14 lb. pressure mentioned in Table 6 was adopted to ensure that no sparking could be attributed to jumping of the brushes.

Dr. Smith has given us a very good statement of the general position of regenerative control at the present time, and I agree with him that it cannot be assumed that regenerative control would necessarily be any benefit in all cases where rheostatic braking is employed. In tramcars and even in battery vehicles, however, it seems to me that much could be done with a device such as this which can be adapted to a standard outfit without interfering with the series-parallel control.

I did not intend to touch on the question of control, but as Mr. Robertson has raised it I may say that I would not suggest any alteration of the standard controller, as this would be a fatal objection to any device for regeneration. It is quite feasible, as shown in the concluding paragraphs of the paper, to start up the motor as a series machine and change its characteristic from series to shunt by closing the transformer primary circuit and the rectifier circuit. A double-pole switch is sufficient for this purpose. The result, then, is that the rectifier boosts up the motor field-current and causes the motor armature to generate current which passes back through the rectifier to the line. This scheme worked quite satisfactorily and gave a large range of speed with one setting of the transformer ratio, and could be used for slowing down cars on the level by returning current to the line. With the same setting of the transformer ratio, greater braking effect can be obtained by changing over the armature connection from the field to the line, giving the ordinary connections used in these tests. This would be done preferably with some resistance in the controller, which would then be cut out gradually to obtain full regenerative effect. It is not difficult to devise a switch not only to perform these changes but also to return everything to normal series-parallel control when the controller handle is moved to the off position, so that in an emergency the rheostatic brake can be brought into action in the ordinary way. Alternatively, stronger regenerative effect can be obtained by reducing the ratio of the transformer, instead of by changing over the armature connection. The switching arrangements would then be very simple indeed. The size of brush required for 40 amperes is only a little more than double the size used in these tests.

The position as regards running at low speeds is quite the reverse of what Mr. Hird imagines it to be. The motor was run as a regenerator at much lower speeds than those given in the tests, but the transformer used had not tappings suitable for making tests at these speeds. They were obtained by using low tappings in the primary, as higher tappings in the secondary circuit were not available. This made the magnetizing current as high as 7 or 8 amperes, and as this current had a demagnetizing effect on the motor field it made the speeds higher than they would have been with suitable tappings, and therefore gave false results. The lowest speed obtainable depends on the saturation point of the motor field, and there is no more difficulty in saturating the field with the rectified current than there is in rheostatic braking. The speed can therefore be brought practically as low as with the rheostatic brake. Although I agree with Mr. Hird that it is not easy to fit slip-rings and brushes in a restricted space, I do not share his point of view. The problem of collecting a small alternating current in this way has scarcely ever arisen, and it involves as much departure from conventional design as the coal-cutter motor does for its success. The space in this motor is less than in many tramway motors, yet no trouble has ensued. Stretched flexible cable was used for collecting the current, but this was merely to save making brush gear and not because brush gear could not have been fitted. My own experience of Renfield-street is that ever since the accident occurred (in which the driver forgot that he had a rheostatic brake) I have observed that many drivers are in the habit of using rheostatic braking in preference to mechanical braking. The question thus arises: Why not regenerative braking?

INSTITUTION NOTES.

Robert Blair Fellowships.

The London County Council have founded two Fellowships, each of the value of £450 and tenable for one year, to enable British students of at least 21 years of age to pursue a course of advanced study or research in Applied Science and Technology in the Dominions, the United States or other foreign countries. The Fellowships are open to suitable candidates who have been trained in Applied Science and Technology, but in making the awards preference will be given to engineering science and to those who have completed a course of study in London institutions or who have been identified with the London teaching service.

Applications for the Fellowships should be made on a prescribed form obtainable from the Education Officer, London County Council, The County Hall, London, S.E. 1, on or before the 30th June in each year.

Current Loading of Paper Cables.

The British Electrical and Allied Industries Research Association have issued in booklet form (Ref. F/T14) the tables of Permissible Current Loading of British Standard Impregnated Paper-Insulated Electric Cables included in the Second Report on the Research on the Heating of Buried Cables which was published in Vol. 61 (1923) of the *Journal*.

Copies of the booklet can be obtained by members of the Institution on application to the Secretary of the Electrical Research Association, 19, Tothill-street, Westminster, S.W., at the reduced price of 9d. per copy.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 May–25 June, 1924 :—

	£	s.	d.
Aikman, A. N. (London)		10	6
Andrews, W. F. (London)		10	6
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Western Electric Company	40	0	0
Williamson, G. E. E. (Derby)		5	0
Wood, L. E. (Bradford)		5	0

* Annual Subscriptions.

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[3] Military mining.
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TRANSMISSION MAINTENANCE OF TELEPHONE SYSTEMS.

By P. E. Erikson, Member, and R. A. Mack, Associate Member.

(*Paper first received* 8*th December*, 1923, *and in final form* 15*th February*, 1924; *read before* The Institution 6*th March*, 1924.)

Summary.

This paper is divided into two parts. The first part deals with the broad aspects of modern telephone transmission maintenance, the economic justification for good maintenance, and the general lines upon which it should be carried out. The second part gives the theoretical considerations leading up to the development of a series of testing instruments, by means of which transmission losses in any part of the telephone system can easily be measured. This part also contains brief descriptions of the instruments and their use.

Table of Contents.

Part I.

GENERAL ASPECT.

During the last three years no less than six important papers * dealing with various telephone problems have been presented before the Institution. The discussions in connection with these papers have clearly shown the interest which an ever-increasing number of the members are taking in the development of the art of

* Sir W. Noble: "The Long-Distance Telephone System of the United Kingdom," *Journal I.E.E.*, 1921, vol. 59, p. 389.
E. S. Byng: "Telephone Line Work in the United States," *ibid.*, 1922, vol. 60, p. 85.
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J. A. Fleming: The Fourteenth Kelvin Lecture: "Problems in Telephony Solved and Unsolved," *ibid.*, 1923, vol. 61, p. 613.

telephonic communication. The importance of this subject is accentuated by the fact that it was made the theme of the Presidential Address in 1922–23 and of the Fourteenth Kelvin Lecture (*loc. cit.*).

A study of the papers and addresses mentioned reveals the fact that, broadly speaking, they all deal with development, design or construction of telephone plant. The transmission maintenance question is referred to by some of the authors, but, as we shall endeavour to show, this phase of the subject is so vital as to warrant a separate study and discussion.

What do we mean by transmission maintenance? In its broadest sense we interpret it to mean not only the upkeep of telephone lines and apparatus from a purely physical standpoint, but the provision of methods and apparatus to guard against the introduction of factors which are detrimental to a satisfactory transmission of speech. The designer of the better class of equipment which goes into a modern telephone system works to certain standards, and this enables the telephone administration to furnish satisfactory transmission of speech. If correctly installed, such a system should therefore theoretically be 100 per cent perfect. Now, it is common experience among telephone engineers that while the plant may be nearly perfect when first installed, deterioration, due to a number of causes, inevitably occurs in time. By way of illustration let us consider a non-loaded long-distance open-wire line 500 miles long with conductors weighing 600 lb. to the mile throughout in its construction. The transmission equivalent of this circuit, between test-boards, would then be about 13 miles of standard cable (measured at a frequency of 800 periods per second). For the purpose of this illustration let it be assumed that the combined losses due to the extensions through the exchanges to the subscribers' premises at each end, amount to a total of 16 miles of standard cable. The total equivalent is therefore 29 standard miles, which may be regarded as satisfactory.

The transmission-equivalent of the open-wire line presupposes normal conditions, that is to say, high insulation, freedom from external influence (such as noise by induction), good conductivity and absence of bridged connections (accidental or otherwise). Now it is to be expected that, in time, any one or all of the conditions mentioned will change and that losses will gradually creep in.

Faulty insulators, an error in the transposition of the line wires during changes or repairs, defective joints or some apparatus or instrument subsequently placed across the circuit at an intermediate point—any one or all of these causes may result in an appreciable increase in the transmission-equivalent. The losses thus introduced may easily aggregate 5 to 10 standard miles.

Furthermore, in the exchanges there are a number of points at which losses may accidentally be introduced. Poor contacts on protector springs, a faulty coil or incorrect wiring have been found to cause losses of as much as 10 to 15 standard miles, with an average of about 2 standard miles or even higher.

If we take the losses which by accident may occur in the open-wire line proper to be of the order of 7 standard miles, and the losses due to defects in the extension lines at each end to be equivalent to 4 standard miles (based on the average of 2 miles cited above), we then have to add 11 standard miles to the original 29 miles for overall transmission. In other words, more than one-third has been added to the original figure, which now becomes 40 standard miles. This, as telephone engineers know, may be regarded as uncommercial speech transmission.

The factors which contribute to this abnormal condition will be dealt with more fully in this paper, but, before taking up the purely technical side of the problem, it will be useful to demonstrate what these losses may mean from an economical standpoint. In the ordinary way, losses which are encountered in commercial life may be expressed in some monetary value and, while in this case such expression is difficult, it is nevertheless possible, by means of an example, to give a fair idea of the considerable sums of money involved.

If, to compensate for losses occurring in a correctly designed plant, it is assumed that the efficiency of some portion of it has to be improved, the cost of such improvement can be taken as a measure of the money value of the losses which were present.

The following example, taken from a paper by Captain J. G. Hines read before the Institution of Post Office Electrical Engineers on 13th November, 1923, illustrates this method:

"It may be stated that in the case of an exchange of moderate size such as Willesden, which is about 7½ miles from the Trunk Exchange, a reduction of one mile S.C.E. in the local line allowance can only be made up on the existing trunk junctions by an additional capital expenditure of approximately £6 600. As there are 100 exchanges of various sizes in the London area, it will be seen that the total expenditure that would be involved by a general reduction of the loss by one mile is very large."

It should be noted that the capital expenditure referred to above could not fully compensate for losses occurring between subscribers' stations and the end of the trunk junctions. The above example is, therefore, more indicative of the money value of losses occurring in plant used only during trunk connections.

A further example serves to indicate the money value of losses occurring in two important items of local plant, namely, "A" position cords and "B" position cords, and illustrates the order of the expenditure necessary to compensate for losses which can be eliminated by the carrying out of transmission maintenance tests.

The figures given below are based upon actual experience of the losses in "A" and "B" cord circuits, which can be detected by the use of a simple transmission measuring-set of a type referred to in this paper. Tests made upon several modern telephone systems have shown that, until detected, approximately 10 per cent of all "A" and "B" cords have abnormal losses. Measurement has also shown that the average abnormal loss upon such cords is of the order of 4 miles of standard cable.

Taking what may be regarded as an average telephone connection involving the use of at least two cords, it follows from the above data that the average accidental

loss, assuming 2-cord circuits involved, would amount to $2 \times 4 \times \frac{10}{100} = 0 \cdot 8$ m.s.c.

The estimation of the value of this loss involves an economic study of some length, but such a study based upon a large telephone system indicates that an average loss of 0·8 mile of standard cable upon the average connection involves an annual loss of approximately 3·2 pence for every subscriber's station in the system.

Taking the round figures of 1 000 000 subscribers' stations for the United Kingdom, this represents an annual loss of about £13 000. Assuming that interest, depreciation and maintenance can be taken at 12·5 per cent of the capital involved, the capital amount corresponding to the above annual loss is £104 000.

When it is remembered that this example takes into account only the losses which are known to occur on but two items of the plant, the saving which can be effected by proper transmission maintenance upon all items can be well appreciated.

We now propose to deal with the transmission maintenance of modern telephone plant. For this purpose we may select as an illustration a telephone system in any progressive country, since the general principles of construction and design are everywhere the same. We have, however, largely taken the American practice as a basis, chiefly for the following two reasons:

(*a*) The telephone development in that country is the highest in the world.

(*b*) We have had an opportunity of studying more intimately the transmission maintenance practices in that country.

We have already briefly referred to the abnormal transmission losses which may develop in a telephone system, impairing its efficiency to a greater or less extent. Before discussing these losses and their causes in detail, it will be advisable to consider the normal condition, that is to say the grade of transmission which should be given in a well-designed system.

For convenience in discussing this broad subject, which, in fact, comprises all of the equipment germane to a telephone plant, we may divide it into two main parts:

I. The exchange area system.
II. The long lines system.

As it would lead us too far afield if we were to consider every piece of apparatus and every circuit in the system, we have confined our study to representative types. The principles are substantially the same for similar portions in the whole system.

I. The Exchange Area System.

In dealing with this part of the telephone system—as distinct from the long lines plant—it is necessary to indicate what elements we are including under this heading. An exchange area, as we are considering it from a transmission maintenance standpoint, is understood to include telephone exchange equipment, used for long-distance operation, for junction working and for local traffic. The losses which occur in the long-distance switchboard circuits, the "A" and "B" cord circuits and associated apparatus (telephone operator's sets, etc.) are dealt with as types, and so are the losses in the circuits of private branch exchanges.

It should be noted that, although we have here described transmission maintenance practices as applicable to manual switchboard equipment, these practices are equally important for machine-switching equipment. Space will not permit a description of their application to the latter, but since the principles are essentially the same for both, a consideration of the manual equipment will, we believe, be sufficient for purposes of illustration.

When operating conditions so demand, telephone repeater equipment is sometimes installed in long-distance telephone-exchange buildings. This type of equipment is not ordinarily classed with exchange apparatus, and, since it requires special maintenance tests, these are described in the part of this paper which deals with long lines. The lines connecting the local exchanges and those extending to the subscribers' premises are, however, included in our study of exchange areas.

It is not intended to describe here the operating features of the equipment involved, as this is well known to telephone engineers, but for the sake of reference the main items of which we are considering the transmission features are further subdivided under two headings: A. Internal equipment. B. External wire plant (local lines).

A. Internal Equipment.

1. Exchange Equipment.

Long Distance Switchboard | "A" Board | "B" Board | Private Branch Exchange

(*a*) Cord Circuits | (*b*) Telephone Operator's Circuit | (*c*) Line Termination Apparatus | (*d*) Protection

2. Subscribers' Instruments (including protection).

(*a and b*) *Cord circuits and telephone operators' circuits.*—All of the above items constitute circuit elements which introduce what might be termed "normal transmission losses" into the exchange area. From various causes, such as mistakes in wiring of the apparatus, faults developing in service (short-circuit of winding or other defects in the apparatus), losses are introduced which, if allowed to remain, would seriously interfere with efficient operation of the circuit. The ordinary maintenance of an exchange area does not provide means for detecting all such losses, and it is necessary to provide instruments for measuring in a rapid routine fashion such parts of the equipment as experience has shown to be subject to defects.

Considering the large number of elements involved, it will perhaps be advisable to select some representative cases indicating normal transmission losses, and illus-

The examples given in Table 1 are the results of actual measurements and demonstrate, beyond any doubt, the importance and need of careful transmission maintenance upon circuits of these types. Testing apparatus is now available which enables tests to be made in a routine manner for the location and elimination of defects which have accidentally developed.

(*c*) *Line termination apparatus.*—The importance of correctly terminating a loaded cable in exchange areas was early recognized. The impedance of a loaded cable circuit is so much greater than that of the non-loaded circuits to which it is connected in service that, unless special precautions are taken, transition losses will occur at the junction.

Repeating coils, having suitable impedance values in their primary and secondary windings, are therefore inserted between the two types of line, with the result

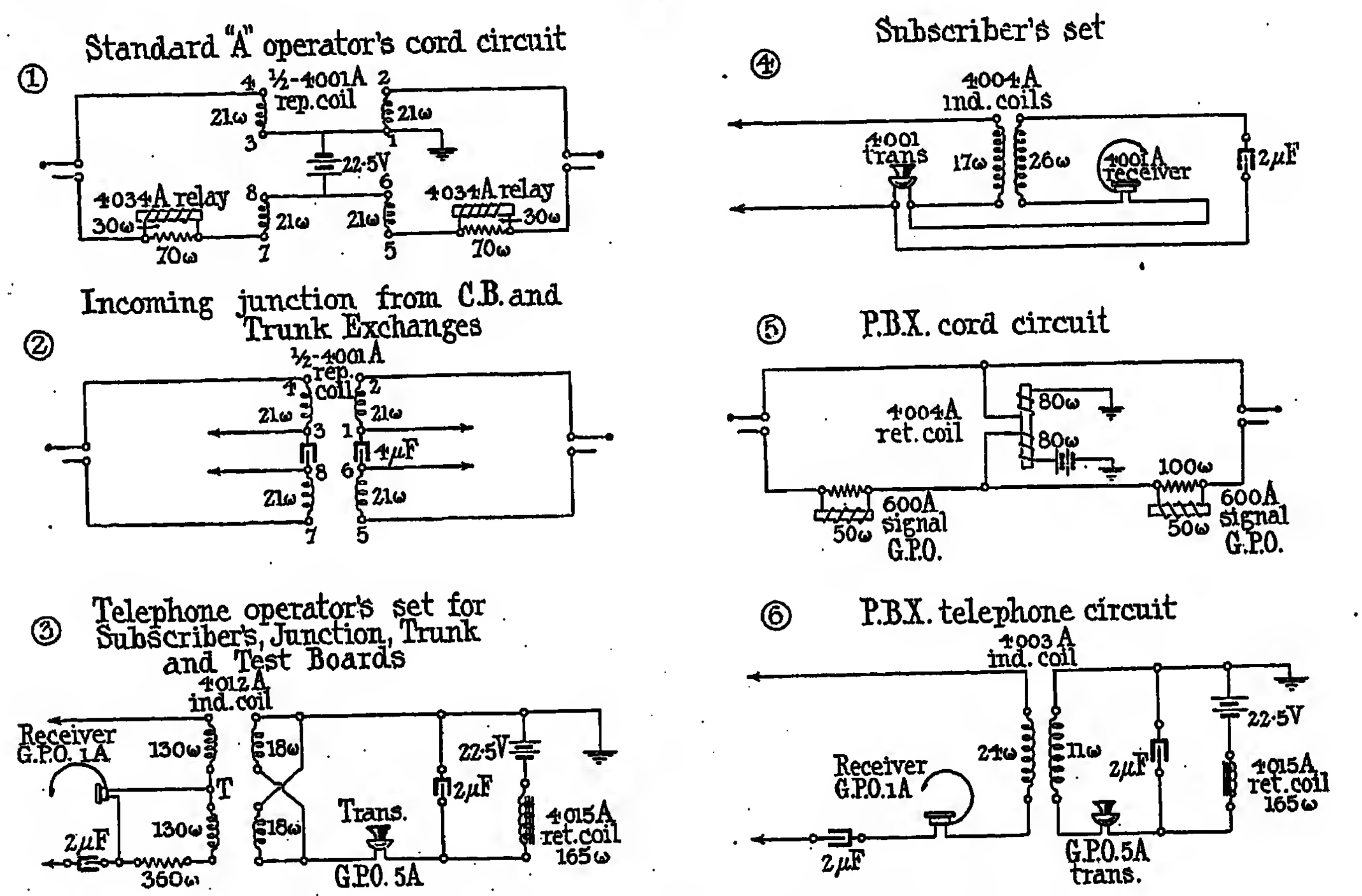

FIG. 1.—Typical transmission circuits in exchange areas.

trate the effects which the defects above mentioned have upon the system as a whole.

In Fig. 1 are shown in diagrammatic form representative manual types of cord circuits for trunk and local switchboards, as well as operators' telephone sets for the same type of equipment. Under normal operating conditions the transmission loss in any one of the circuits shown is bound to vary, but having obtained sufficient test data it has been possible to establish an average value and also a maximum (limiting) value, the latter being intended to indicate the point beyond which abnormal losses may be suspected. As a matter of interest Table 1 gives the values for the circuit shown, the figures being arranged in three columns. The first column shows the average loss, the second column the limiting value, and the third column abnormal loss, the cause of which is recorded in the column headed "Remarks."

that the transition losses are materially reduced. It follows that if, by mistake, a repeating coil of incorrect impedance ratio is inserted, this loss may be materially increased.

For the purpose of illustration let us take the case of a cable circuit, loaded at intervals of 1⅝ miles with coils having an inductance of 175 millihenrys. Assume that this cable terminates in a non-loaded loop of 20-lb. conductor, say 1½ miles in length. With the proper type of repeating coil, the total transition loss will amount to about 0·7 mile of standard cable. Now suppose an ordinary repeating coil, having a unit impedance ratio (1 : 1), is placed in the circuit. The total losses would then amount to 1·8 miles of standard cable. Thus a loss of 1·1 miles of standard cable has accidentally been added to the circuit.

Again, take the case of a loaded cable circuit which is designed for long-distance operation with telephone

repeaters. If, as frequently happens, the cable has to enter a repeater station through a repeating coil, then it is necessary (in 2-wire operation) to insert a coil of similar characteristics on the corresponding " network " side of the circuit in order to obtain the necessary balancing condition. The " line " coil and the " network " coil must have the same electrical characteristics, within very close limits, otherwise the gain obtainable by means of the repeater is seriously affected.

(*d*) *Protection.*—In regard to protection apparatus, more particularly that installed in a telephone exchange, experience has shown that trouble is caused by excessive contact resistance between the heat-coil contact surfaces and the protector springs, as well as between the protector springs and their assembly bolts. Trouble from this source usually appears as line noise, which is detrimental to transmission, but it may also result in a direct transmission loss, which can economically be eliminated.

Where the length and importance of the junction cable circuits warrant it, their transmission efficiency may be improved by loading.

(1) Grade of Transmission.

Before discussing the broad aspects of the maintenance of this part of the exchange area plant, brief references will be made to some considerations governing the transmission standards which should be aimed at in a well-designed system.

The circuits to be considered are:

(*a*) Subscribers' lines (to the local exchange).
(*b*) Junction circuits (connecting ordinary exchanges).
(*c*) Trunk switching circuits.
(*d*) Order wire circuits.

(*a*) *Subscribers' lines.*—The choice of conductors for this class of circuit is necessarily based on the limiting loop resistance for each exchange area, as determined

Table 1.

Ref. No. in Fig. 1	Description of circuit	Average loss	Limiting loss	Abnormal loss	Remarks (Cause of abnormal loss)
		Miles of standard cable			
1	Standard " A " operator's cord circuit	1·4	2·0	5·4	Non-inductive relay winding disconnected
2	Incoming junction circuit	0·7	1·4	11·5	4-μF condenser disconnected
3	Telephone operator's set	3·5	4·8	5·0	350-ohm resistance short-circuited
4	Subscriber's set *	4·0	4·5	8·9 8·7	17-ohm winding reversed 26-ohm winding reversed
5	Private branch exchange cord circuit	1·2	1·5	4·1	Non-inductive relay winding disconnected
6	Private branch exchange telephone circuit	1·2	1·5	7·3	Induction coil windings interchanged

* Transmitting loss.

Note.—1, 2, 3, 5 and 6 are measured as bridge losses in the circuit.

The winding of the heat coil, which is in series with the line, is designed to have a resistance of the order of 3 to 4 ohms. A poor contact may add 1 ohm, or more, to this resistance and it is quite evident that a loss due to this cause should be prevented.

(2) Subscribers' Instruments.

Considerable attention has recently been given to this part of the local line plant, and it is believed that development work now in progress will result in simple and inexpensive means being provided for checking the efficiencies of subscribers' transmitters and receivers after the latter have been put into service.

B. External Wire Plant in an Exchange Area.

The circuits which connect the subscriber with his local exchange (usually referred to as " the subscribers' loop "), as well as those interconnecting the various exchanges in a modern telephone system, are usually carried in lead-covered cables (aerial or underground).

by a fundamental plan study. Different lengths of subscribers' loops require different sizes of conductors in the cable, but, generally speaking, it has been found economical to standardize the sizes of conductors in a cable and, ordinarily, 3 sizes of conductors are used, namely:

British Standard (nominal weight of conductor per mile)	American Wire Gauge (B. & S.)	Diameter, in mm.
20 lb.	No. 19	0·91
10 lb.	No. 22	0·64
6½ lb.	No. 24	0·51

The use of a still smaller size, namely, No. 27 B. & S. or 3¼ lb. conductor (0·36 mm), has been considered for short subscribers' loops in congested areas. In some instances it has been found economical to combine two

sizes of conductor in the same subscriber's loop. On account of the circuit density near exchanges, and the consequent duct congestion, the smaller size has usually been placed at the exchange end of the loop.

For reasons inherent in the size of the exchange area or the natural growth of a community, it happens that a few loops exceed the limiting resistance contemplated in the fundamental study. Special methods may have to be resorted to, such as the use of auxiliary batteries on the subscriber's premises, parallel working of pairs where spares are available, etc.

In order to give some idea of the magnitude of the normal losses in subscribers' lines it may be stated that from 4 to 5·5 miles equivalent in standard cable may be regarded as good practice. The loss, as stated, represents the mean value of the sending and receiving losses when referred to a circuit, using a standard common-battery instrument and zero subscriber's loop.

These subscriber's line losses can be related to the resistance of the subscriber's loop in accordance with the following table:

transition losses at the exchange end can be materially reduced by means of suitable transformers.

(*c*) *Trunk switching circuit.*—Strictly speaking, this circuit is part of the long-distance (trunk) plant and, as such, it is therefore important that the transmission losses should be reduced to as low a value as it is economically possible to produce.

The standard of transmission which has been found desirable is such that the equivalent of the circuit should be from 1·5 to 3 miles of standard cable. Where the circuit is of sufficient length, it may be loaded, the conditions in this respect being substantially the same as for the long junction circuits.

(*d*) *Order-wire circuits.*—Good transmission over order-wire circuits is important for maintenance of proper standards of service. For example, although the telephone operators using these circuits are trained listeners, the passing of a wrong number may occur because of reduced efficiency of the line. Repetition and consequent waste of operating time follow, to the detriment of the service.

TABLE 2.

Type of cable used			Subscriber's line losses	
Conductor	Mutual capacity		4 standard miles	5·5 standard miles
	μF per mile	μF per km		
20-lb. (0·91 mm)	0·085	0·053	170 ohms	240 ohms
10-lb. (0·64 mm)	0·083	0·050	190 ohms	280 ohms
6½-lb. (0·51 mm)	0·078	0·048	220 ohms	325 ohms

The question of loading subscribers' loops to improve transmission has been considered. The improvement obtainable by this means is not very great, chiefly because the impedance of the subscriber's set and the repeating coil both have a positive reactance. Furthermore, no gain is secured by this method in the battery supply, which forms a major part of the loss in long subscribers' loops.

(*b*) *Junction circuits.*—Junction circuits are less in number and generally longer than subscribers' loops, and can therefore economically justify a higher grade of construction. Cable conductors up to 40 lb. per mile in weight have been used, while 20-lb. conductor circuits are quite generally used. Under certain circumstances loaded 10-lb. conductors are used, as described below.

The allowable transmission loss in junction circuits in a well-designed exchange area may fall between 7 and 10 miles of standard cable, and should not exceed the latter figure. These values are, however, not to be regarded as absolute figures, as they are dependent on other factors, notably the limiting loop resistance and the general standard of transmission adopted for the system.

It has been found economical to load junction circuits in the case of long 20-lb. and 10-lb. conductors. The

During busy hours it frequently happens that 4, and in some cases as many as 6, "A" operators come in simultaneously on an order wire. In the former case the added loss in transmission is about 9 miles of standard cable; in the latter case about 12 miles of standard cable are added to the loss in the order-wire.

The total equivalent of any order-wire, from operator to operator, should not exceed 20 miles of standard cable. Experience has shown that with this allowance very little trouble is caused, but as soon as it is exceeded complaints are quickly forthcoming.

(2) TRANSMISSION MAINTENANCE.

The upkeep of junction and subscribers' lines for the purpose of ensuring good transmission differs only in degree from that required for the long lines.

(*a*) *Direct-current tests.*—In all cases where a cable has been installed it is customary to make tests for insulation resistance and direct-current resistance and so to establish records of the condition of the circuits. The results of these tests, and particulars of the size (or sizes) of conductors, number of pairs, etc., are usually entered on cards which are kept for reference at the exchange.

Periodic tests are then made for the purpose of

checking the above results. The insulation test is particularly useful as an indicator of the general condition of the cable. Changes noted in this respect during successive tests may enable incipient troubles to be detected and corrected before the cable becomes commercially unfit for service.

(*b*) *Tests on loaded circuits.*—In addition to the above-noted tests, it is good practice to ascertain from time to time the condition of the loading coils. A means to this end is the line impedance bridge described on page 676 and shown in Fig. 17.

(*c*) *Transmission tests.*—The transmission-equivalents of a junction circuit can best be measured from the main distributing frame. The No. 1-B transmission set described on page 671 provides a rapid and reasonably accurate means for this test. If great accuracy is desired, tests may be made, using the No. 3-A transmission measuring set. The former method necessitates the looping of the circuit and consequently a " triangulation " test, in order to obtain correct values for the individual circuits.

II. THE LONG LINES SYSTEM.

General.

The first telephone line was the best telegraph line of the day, consisting of a single iron wire with an earth return. It soon became evident that this type of line was unsuitable for telephone operation, partly on account of the disturbances which arose from the earth connection and partly on account of the inferior transmission qualities of iron wire.

The introduction of the double-wire copper circuit eliminated to a considerable extent both of these defects. Early investigators showed the way to the elimination of mutual interference when several telephone circuits were placed on the same pole line. The various systems of transposing telephone wires have all been developed as a means not only for the prevention of cross-talk between telephone circuits, but also to reduce interference from neighbouring telegraph and power circuits.

In recent years the construction of high-tension power lines for industrial and railway purposes has necessitated further precautions to safeguard the communication circuits against external disturbances. In this connection we may mention the important work carried out in California on behalf of the California Railroad Commission by a Joint Committee of power and communication engineering experts. The investigation lasted nearly five years and the recommendations of the Committee are contained in a series of technical reports subsequently issued by the Railroad Commission of the State of California on 1st April, 1919 (California State Printing Office, Sacramento, 1919).

The history and development of the phantom telephone circuit formed part of the subject of a recent paper before the Institution.* The successful operation of the phantom circuit is rendered possible only by a careful maintenance of balanced line conditions and suitable transpositions of the wires.

Then we have Pupin's epoch-making invention which, with the work of G. A. Campbell and others, gave the telephone engineer a practical solution of Heaviside's theory of the need of increased inductance in telephone circuits for the improvement of transmission. The application of the loading coil to open-wire telephone lines extended the talking range of this class of circuit to a distance of 2 200 miles (New York–Denver), the longest non-loaded open-wire line up to that time (1912) being about 1 000 miles.

Paper-insulated telephone cables had been in use several years before the loading coil was commercially developed, but the distances which they could cover from a telephone transmission standpoint were necessarily limited. To-day, the loading of cables for long-distance telephony is being adopted in all countries where the service justifies it, because the development of balanced cables and loading coils has long been recognized as a commercial success.

The latest stage of development is, of course, the introduction of the telephone repeater into the long-distance telephone plant. In their paper on " Telephone Repeaters " before the American Institute of Electrical Engineers, Messrs. Gherardi and Jewett give an excellent account of the subject. Sir William Noble in his paper before the Institution on " The Long-Distance Telephone System of the United Kingdom " illustrates the economies to be expected as a result of the adoption of the telephonic repeater in the cable system of the British Post Office. Mr. Gill in his Inaugural Address points the way to the solution of the international telephony problem, the solution being largely founded on the judicious use of the telephone repeater.

The outside line plant of a large telephone system represents by far the greatest proportion of the capital investment, and it is therefore not surprising that every effort is made to utilize it to the utmost of its capacity.

One of the latest achievements in this respect is the successful adaptation of the principle of carrier-current transmission, which enables several telephone conversations to be carried over the same metallic circuit. This subject is covered in a very comprehensive paper read in 1921 before the American Institute of Electrical Engineers by Colpitts and Blackwell.* Mention should also be made of two prominent papers presented to the American Institute in August 1922, namely, " Telephone Transmission over Long Cable Circuits," by A. B. Clark, and " The Philadelphia–Pittsburgh Section of the New York–Chicago Cable," by J. J. Pilliod.†

This brief survey of the development of the long lines transmission problems gives, we believe, a fair idea of the need for means to fulfil the more and more exacting requirements in regard to the proper maintenance of the transmission service. It has been shown that ever greater distances are being conquered, with consequent greater demand on a widely separated staff responsible for the operation of a complicated system.

If we consider a country-wide telephone system such as that represented by the long lines in the United States or Great Britain, we find all the industrial and commercial centres linked up by important telephone

* J. G. Hill: "Phantom Telephone Circuits, and Combined Telegraph and Telephone Circuits, worked at Audio Frequencies," *Journal I.E.E.*, 1922, vol. 60, p. 675.

* *Transactions of the American Institute of Electrical Engineers*, 1921, vol. 40, p. 205.

† *Ibid.*, 1922, vol. 41, p. 446.

lines. By far the greater portion of these lines are, as yet, made up of open-wire construction, although long-distance cables with their greater immunity against "breakdowns" are rapidly coming into use, where economic considerations demand it.

The weight of the copper wires in overhead lines economically limits the distance over which commercial speech can be carried.

A glance at Table 3 shows the limitations in this respect. For the purpose of this illustration a 15-mile equivalent (between test-boards) has been assumed.

tion of the system as a whole. The control of the circuit as a working unit, and the responsibility for securing a specified transmission-equivalent, must rest with one station selected for that purpose.

It may be of interest to outline the procedure which is followed in this respect, taking as an example a section of the transcontinental line above referred to. This circuit passes through Chicago on its way west, and between the two cities, New York and Chicago, there are three repeater stations, indicated by crosses in the diagram below.

Chicago		Beaver Dam		Brushton		Harrisburg		New York
O	295 miles	X	248 miles	X	207 miles	X	181 miles	□

It is to be noted that the lines referred to are not loaded. In the United States the greatest weight of open-wire lines which it has been found economical to improve by loading consists of about 175-lb. conductors. The problem of maintaining a sufficiently high insulation on large open-wire conductors has confined the loading to gauges below the one just mentioned.

Furthermore, it was found that when repeaters were installed on loaded open-wire lines some difficulties were experienced in maintaining, at all times, a sufficiently close balance between the loaded line and its network.

TABLE 3.

Non-loaded Open-wire Circuits.

Weight of copper wire in aerial construction	Diameter of conductor	Maximum distance between test-boards	
lb.	mm	miles	km
800	5·68	720	1 160
600	4·92	570	920
400	4·02	410	660
300	3·48	325	525
200	2·84	230	370
100	2·01	130	210

The loading of a circuit also reduces the speed of propagation and limits the frequency-spectrum, which, in turn, affects the quality of the speech. It has therefore been found more desirable to limit the use of loading coils on open-wire lines and to obtain the desired grade of transmission by means of repeaters alone.

In fact, the transcontinental line (New York–San Francisco) which was originally loaded and so operated with repeaters has since been "unloaded," and repeaters have been installed at more frequent intervals.

We may therefore regard the long-distance system as sections of high-grade lines, located between repeater stations or connecting the latter with terminal cities.

UNITY OF CONTROL.

It would obviously not be practicable to depend solely on the maintenance of the individual sections (i.e. between repeater stations) for the successful opera-

(1) *Repeater gain test.*—The control station (Chicago) makes a roll call and requests the repeater stations to measure the repeater gains, to make vacuum-tube rejection tests (described on page 662) and to report the results at the expiration of 5 minutes. The control station then obtains the reports, starting with Beaver Dam. No record is made of this report; the repeater stations merely state that everything is in order, or, if not, they state briefly the apparent nature of the trouble.

(2) *Balancing test* ("21-*test*").—The control station requests New York to terminate the circuit at the measuring unit with a non-inductive resistance, equivalent to the impedance of the circuit. Brushton is instructed to turn both potentiometers on the repeater set to zero, and Harrisburg is told to make an impedance unbalance test (described on page 663 as "21-test") in both directions. Beaver Dam is likewise instructed to make the same test, the circuit at Chicago having meanwhile been closed through a suitable impedance. Five minutes is allowed for these tests, at the expiration of which Beaver Dam reports. Brushton is then requested to restore the circuit to normal and to obtain the test result from Harrisburg. In turn, New York, Brushton and Chicago then make impedance unbalance tests, for which a time interval of 5 minutes is allowed. The circuit is then restored to normal condition and the results of the last-mentioned tests are reported to the control station.

(3) *Talking test.*—An overall talking test is made between Chicago and New York, using standard subscribers' sets at both ends.

(4) *Transmission test.*—Using a frequency of 1 000 cycles per second the transmission equivalent of the circuit between Chicago and New York is measured. The repeaters at the intermediate stations are set at their specified gains and the circuit is tested on the "straight away" basis, i.e. using the transmission measuring sets described on page 672.

(5) *Ringing test.*—The last test to be made is a ringing test between New York and Chicago. This test is made in both directions, so as to ensure that the signalling apparatus is working properly.

The attenuation loss in each line section is a fixed quantity, and its magnitude is determined from purely economic considerations. In aggregate, these losses are quite considerable when several sections are used in

tandem for long built-up connections. The function of the repeater is, of course, to reduce these losses and bring the transmission circuit down to an equivalent which will permit of commercial speech.

In his Inaugural Address Mr. Gill gave a striking example of the condition which will arise if the gains obtainable by means of repeaters are not maintained at their specified values. As the example which he gives has an important bearing on the question of long lines transmission maintenance, we quote it below *in extenso*:

"When repeaters are in operation, they must maintain constant the gains to be given out or there will be serious effect on the speech. If we assume a 4-wire circuit between Rotterdam and Milan, 500 miles (810 km) long and having five repeaters in it, operating at gains of 23, 30, 30, 30 and 23 standard miles (S.M.) respectively, say an average of 27·2 each, we need only consider what will happen if the gains fall off, since the gains will originally have been set to be as high as safely allowable. Assume, then, that the line without repeaters has a net equivalent of 148 S.M. from which we deduct the repeater gains, 5 × 27·2 = 136, leaving the net loss = 12 S.M. Now suppose the gain at each repeater station for any reason at all falls off by 2 per cent; this will represent 0·54 S.M. each, or 2·7 S.M. for the five stations, and the net result will then be increased from 12 to 14·7 S.M., an increase of 23 per cent in the loss in the line. Should the gain on each repeater fall by 7·5 per cent the total additional loss will be 10·1 S.M., and the final net loss will be increased from 12 to 22·1 S.M.—an increase of 84·5 per cent. In this case the loss would be so great that probably the line would become unworkable. I have chosen these examples to show the importance of uniformity of construction, uniformity of maintenance, and uniformity of operation; it will be seen afterwards what is their particular application. The examples are rather understated than exaggerated; it would have been quite reasonable to have taken a case with 20 repeater stations in tandem, and, furthermore, the gain given by a repeater would not in fact be one definite figure for all frequencies."

The problem of long lines transmission maintenance may therefore be separated under two headings:

(A) Repeater station maintenance.
(B) Repeater line section maintenance.

In practice, all the tests required for both (A) and (B) are carried out either from the repeater station or from a terminal station. It will therefore be convenient to describe briefly the nature of these tests and the practical methods used in applying them to the system as a whole.

(A) Repeater Station Maintenance.

In order to ensure at all times efficient and reliable service, it is very important that a definitely established maintenance routine should be carried out, and periodic tests made upon the various elements which go to make up a repeater station.

For this purpose certain testing equipment is always included in repeater stations, consisting of suitable voltmeters and ammeters for the purpose of checking the normal operating voltages and currents in the repeater circuits. The testing equipment also includes means for determining the transmission gain which the repeater gives in service. There are also separate testing circuits for the signalling operations, which have to be verified from time to time.

The tests which have to be made may be grouped under the following five headings:—

(1) A daily test of the battery circuits to check the proper values of currents and potentials.
(2) A periodical test to ascertain that the ringing and switching relays in the various circuits work properly.
(3) A monitoring test upon commercial calls. Such tests should also be made periodically on through line repeatered circuits.
(4) A transmission test on the repeater should be made at least once a week, to ensure that it is giving the desired transmission gain.
Further and more complete gain tests should be made periodically on all repeater units.
(5) The vacuum tubes should be periodically tested, so that they may be replaced when they show any signs of ageing.

(1) *Battery test.*—The change in the actual gain of a repeater is due to the battery variations, and, in order that the repeater gain may be kept constant, definite limits have to be placed on the voltages of the three batteries.

In regard to the tests of the batteries in repeater stations, suitable instruments are provided on the power switchboards associated therewith. It is therefore an easy matter to check the voltages of (*a*) the battery which supplies the current to the filaments of the repeaters; (*b*) the battery which supplies the anode potential to the vacuum tubes; and (*c*) the battery which supplies the grid potential to the vacuum tubes.

In addition to these tests a further check is obtained by measuring the filament current, the space current and the grid potential, on instruments mounted on a separate panel on racks conveniently located in regard to those supporting the repeater panels proper.

In the latest type of vacuum tube using oxide-coated filaments the current under normal operation should be 0·97 ampere. This current is allowed to vary between 0·94 and 1·0 ampere. Fig. 2, which applies to a typical tube, indicates how the gain of the repeater is practically independent of the filament current, except for values outside the above limits.

The voltage of the plate battery is normally made 130 volts positive to the negative end of the filament. Small changes in this voltage do not affect the operation of the repeater to any great extent. A serious variation would, however, result in a considerable change in the gain. The limits are therefore fixed at 125 volts minimum and 135 volts maximum.

The grid is maintained at 9 volts negative to the negative end of the filament. The limits imposed on the grid battery are such that the grid voltage does not

vary by more than $\pm \frac{1}{2}$ volt from the mean value 9 (volts).

If the grid voltage falls below its correct value the gain and space-current are increased, and this may be accompanied by a sacrifice in quality.

The three effects enumerated above may be cumulative and it is therefore necessary, in placing operating limits on repeater station batteries, to consider all three cases simultaneously. This consideration results in imposing narrower limits on the batteries than are required by an individual case. It is this consideration which fixes the lower limit of filament current at 0·94 ampere.

It will be noted that, in fact, very little change in gain occurs until the filament current falls below 0·9 ampere. When the current falls below 0·85 ampere the gain decreases very rapidly.

The upper limit of the filament current is imposed

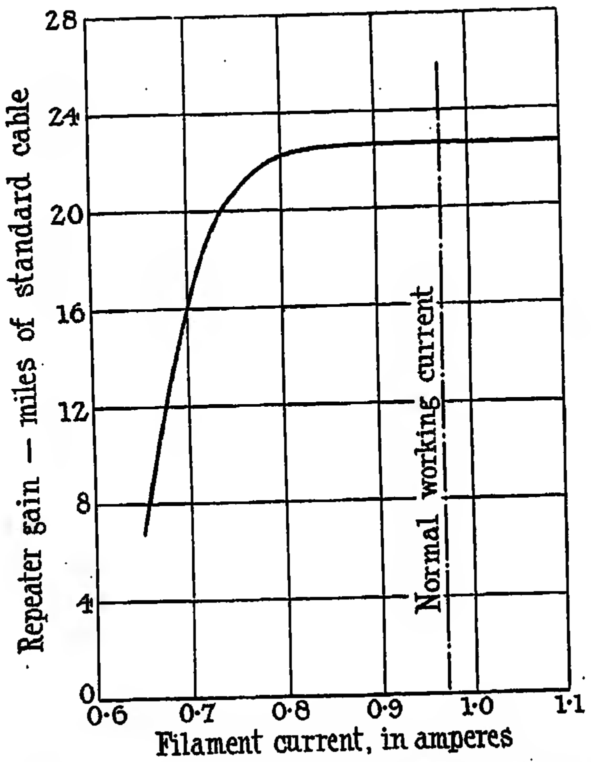

Fig. 2.—Characteristics of vacuum tube having oxide-coated filament.

for a different reason. As may be seen from the curve, the tubes would work well with a much higher filament current but the life would be considerably shortened. For example, at 1·25 amperes the life is reduced by something like 80 per cent. From these considerations an upper limit of 1 ampere is therefore fixed.

(2) *Ringing tests.*—These should be made under actual operating conditions, that is to say, outgoing signals intended for the distant station should be supplied on the line jacks on the toll switchboard, and incoming signals from a distant station should be received in the same manner as for an ordinary long-distance call.

The low-frequency (16 or 20 cycles) signalling apparatus for the repeater circuit is generally so arranged that during the ringing interval the telephone repeater is rendered inoperative. When 135-cycle frequency signalling is used, the ringing current is, when necessary, allowed to pass through the vacuum tube in order that it may be amplified before being allowed to pass through the repeater station. When testing the low-frequency signalling, the repeater attendant should listen-in on the repeater circuit during the ringing interval, when the changes in the repeater circuit, caused by the operation of the signalling relays, can be heard in the receiver. In this way the proper operation can easily be verified. If it is found that the signals do not come through in the proper manner, the relays associated with the signalling equipment should, of course, be adjusted.

(3) *Monitoring tests.*—These need no further comment, except that the equipment which is used by the repeater attendant should be so designed as to introduce a minimum transmission loss when in operation. It is customary, therefore, to arrange the coils, by means of which the test is carried on, so that they take off a very small portion of the amplified output of the repeater unit.

(4) *Transmission tests.*—In order to measure the gain which the repeater is giving, a special gain-measuring set is included in the modern telephone repeater station. Gains varying from zero up to 46 miles of standard cable can be measured with a set with a precision of $\pm \frac{1}{4}$ mile. A description of the measuring set may be of interest and is therefore given on page 674.

The normal gains which repeaters are required to give should be specified as determined by the circuit lay-out work when the repeaters are installed. These repeater gains should never be changed by the local repeater attendant except on instructions from the office which has control of the transmission efficiencies of the trunk circuits on which the repeaters are operated. Tests should be made weekly for both the "East" and "West" amplifier circuits at the working potentiometer steps.

Gain calibration should be made on all repeaters periodically, and these calibrations should be used to check the weekly gain measurements. These calibration measurements are made to ensure that the gain-frequency characteristic of the repeater is correct, and to check the functioning of the filters.

Measurements should be taken at least every six months and should be made preferably at the normal working steps at the following frequencies: 200, 1 000, 2 000, 2 500 and 3 300 cycles.

The single-frequency measurements made weekly at 1 000 cycles and checked by the half-yearly figures are used in connection with line-balance tests and also as an indication of any incipient trouble in the apparatus or vacuum tubes.

(5) *Vacuum-tube rejection tests.*—In order to determine whether or not a vacuum tube is defective, a direct measurement of the repeater gain should be made by means of the precision-gain measuring apparatus. Tubes are taken out of service when the variation in gain between the allowable current-limits stated above is greater than one mile of standard cable.

(B) Repeater Line Section Maintenance.

The well-known type of telephone repeater designed for ordinary 2-wire circuits depends for its proper operation on an accurate balance between the line section and its equivalent network. So long as the

network impedance simulates that of the line with sufficient accuracy, the repeater will give the desired gain. Well-designed networks may, in general, be depended upon to maintain their original constants, but the line is subject to changes from various causes, with resultant changes in its impedance. Variation of insulation on open-wire lines, or a faulty loading coil in a cable—to mention two instances—will affect the impedance of the line and cause sufficient variation to prevent the repeater from being operated at its desired efficiency. Means for detecting such irregularities have been developed and will be briefly referred to.

The tests described below refer specifically to loaded cable sections, although they apply, in general, to open-wire lines as well. The requirements relating to insulation tests would necessarily be somewhat modified to meet special conditions.

(1) *Insulation-resistance and continuity tests.*—Although these tests and their object are well known to telephone engineers, their importance warrants a reference to their application on loaded cable (repeater) sections. Generally speaking, if a high insulation resistance is maintained at all times, fault location is greatly facilitated. Also, continuous vigilance in this respect will have its reward, since even a slight decrease in insulation resistance is a danger signal which gives the attendant an opportunity of investigating any incipient trouble before the cable circuit becomes unfit for service.

Good maintenance practice demands that the following routine be observed in regard to the two types of test mentioned :—

The standard voltmeter-deflection method is recommended and the test can most conveniently be carried out from the test-board at the repeater or terminal station.

The insulation resistance should be tested between cable pairs and between each wire of a pair and earth. This test should be made daily on all pairs not in service, and fortnightly on all cable pairs in service.

The continuity test should be made once a week on all cable pairs not in service. This test is not necessary on cable pairs in service, but can, if desired, be made during the fortnightly test for insulation.

(2) *Line impedance test.*—The most obvious method of determining the condition of a line section is, of course, to measure its impedance over a suitable range of frequencies. The apparatus required for this purpose may conveniently take the form of an alternating-current Wheatstone bridge, the operation of which is well known.

This method, although very accurate, has the disadvantage that it is rather slow. To test one circuit over a range of frequencies from 200 to 3 000 cycles per second in steps of, say, 60 cycles takes up the best part of an hour and, if a large number of circuits have to be so tested, considerable time is consumed.

More rapid tests have been devised which enable the operator to determine, with a fair approximation, the condition of the line. These tests in no sense replace the impedance/frequency test, which yields valuable information, particularly in the location of line irregularities. One of these tests, known as the "singing point test" (or 21-test), will be described, as it possesses several advantages.

(3) *Singing point test (21-test).*—As is well known, the operation of a 2-element 2-wire repeater is only made possible by balancing the line in the two directions by a network, which simulates the impedance of the line at all essential voice frequencies.

If the repeater is a 21, or 2-way 1-element type, the degree of balance between the line and its balancing network can be expressed in terms of the gain necessary to make the repeater sing. This gain is the actual effective gain given by a 21-type unit to a circuit, and is equal to the calibrated gain as measured on a gain-measuring set. As shown in Fig. 3, this gain g is equal to the actual gain of the element G minus the loss due to two divisions of energy at the output transformer. This latter loss is $2 \times 3{\cdot}2$ standard miles $= 6{\cdot}4$ standard miles plus the actual coil loss, the total being approximately 7 standard miles. Hence $g = G - 7$. With coils as actually used, the inherent loss is about $0{\cdot}6$ standard mile.

For singing to occur, the gain G must equal the

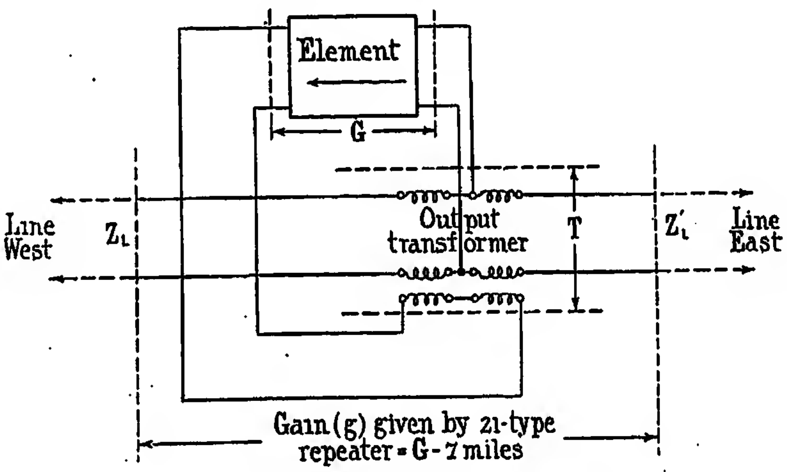

Fig. 3.—Diagram of "21" type repeater circuit.

transmission loss T due to imperfect balance between line "east" and line "west,"

$$\text{i.e. } G = T, \quad \text{or} \quad g = T - 7$$

From this a new definition of singing point is obtained, namely, the transmission loss across a 3-winding transformer minus 7 S.M.

If this result is applied to a 22-type circuit when arranged for a singing point test as given below, it will be found that $T - 7$ is equal to the sum of the calibrated gains of the two potentiometer settings plus 7.

Fig. 4 is a simplified diagram of the "22" type repeater circuit. In describing the method of procedure of making the "21" circuit test, reference will be made to this figure.

To test the balance existing between the east line and its balancing network, the repeater is disconnected from the west line by placing a short-circuit plug in the repeater "line jacks west" and the west network is removed by inserting an open-circuit plug in the repeater "drop jacks west." It will now be seen that the output transformer is so arranged that it will operate as an ordinary repeating coil. This connects the output of repeater No. 2 to the input of repeater

No. 1, forming a "21" circuit involving both repeaters. The singing point should now be determined by monitoring on the repeater set and increasing the gain, step by step, until singing occurs.

The dials of the two potentiometers should be moved up alternately so that they are always within one step of each other, and preferably on corresponding steps. When singing occurs, the readings on both dials are noted. The reading found in this manner has arbitrarily been called "plus poling."

The test is then repeated with the position of the plugs interchanged as regards their positions in the "west" line and "drop" jacks. This latter reading is called "negative poling."

The lower of the two readings obtained as described above is the more representative one, and is used in all cases.

When the unbalance current returns to the input terminals of the 3-winding transformer, it may or may not be in phase with the original current entry. When this return current is directly in phase, the cumulative result will be greater than when it is out of phase. For this reason two polings are taken, one of which will bring the return current more nearly in phase with the original current than the other, and will therefore give a lower singing-point reading.

The calibrated gains used in obtaining the singing-point are obtained from the weekly tests mentioned in a previous section of this paper.

(4) *Impedance unbalance test.*—In the "21" test the singing point is observed at the particular frequency at which the repeater system sings most readily, i.e. the frequency at which the impedance unbalance between the line and its network is greatest.

A method has, however, been developed which enables the singing point to be accurately determined at any desired frequency. This method and the particular testing designed for these purposes are described later in this paper.

(5) *Overall transmission test.*—These measurements should be made from test-board to test-board between the two terminals of the circuit, either on a loop or direct measurement (i.e. without the aid of a return loop) basis as discussed below.

(*a*) *Direct measurement of transmission.*—The circuit which it is desired to test should be connected to transmission measuring sets at both terminals. The terminal office in charge of the test can make arrangements with the distant terminal over the regular traffic channels. Measurements should be made in both directions, one station sending while the other receives, and vice versa. At the sending station the impedance of the sending element should be adjusted to fit the impedance, at that station, of the line which is being measured. At the receiving station the impedance of the receiving element should be adjusted to fit the impedance of the receiving end of the line, and also the impedance of the sending element should be adjusted to match the impedance at the sending end of the line in order that the receiving set may be properly calibrated to take account of differences of impedance, if any, between the two ends of the line. A more detailed description of this test, and the apparatus therefor, is given later in the paper.

(*b*) *Loop transmission testing.*—Where there is no transmission testing equipment at the distant office, it will be necessary to make measurements by looping the circuits back at these offices. Measurements should be made in both directions over the loop with the impedances in the sending and receiving elements of the measuring set adjusted to fit the impedance of the line being tested.

The measurements thus made will give an equivalent for the loop which involves two circuits. In order to obtain the value of each individual circuit it will be necessary to make three loop measurements on three circuits and to compute the value for each circuit from this triangulation.

Of the two methods described above, the first is by far the simpler to handle from both a testing and a traffic point of view. Fewer measurements are involved, and only the circuit under test has to be given up by the traffic department.

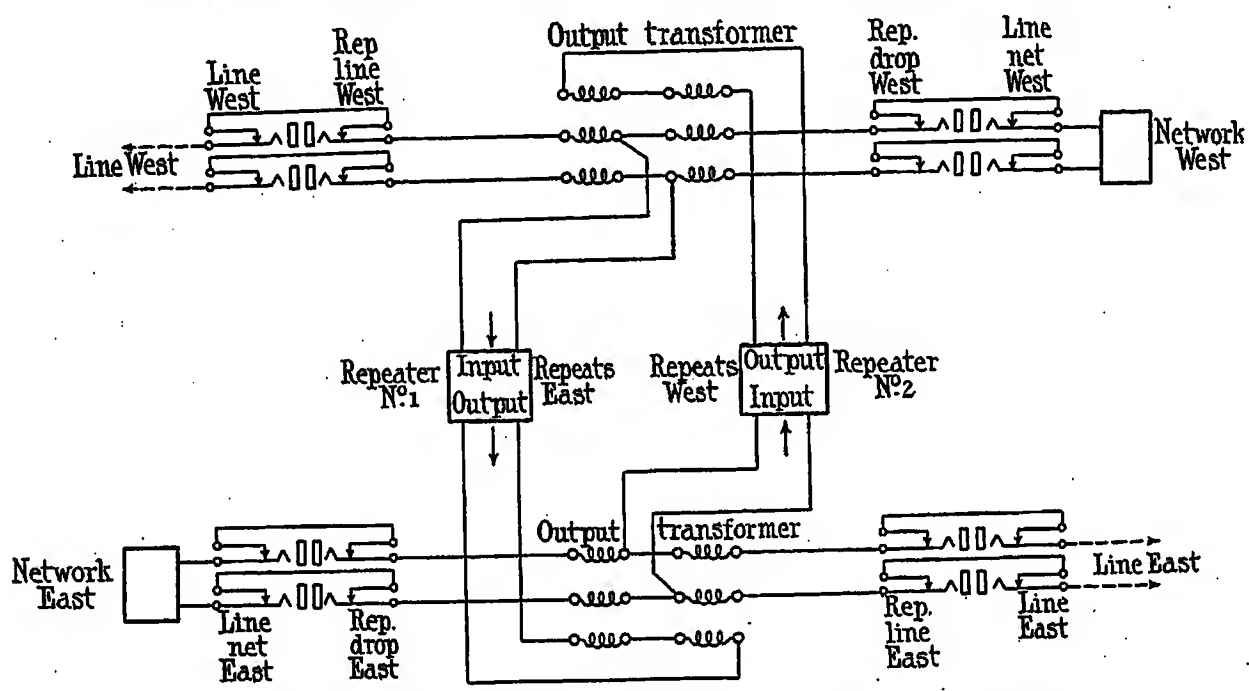

FIG. 4.—"22" type telephone repeater circuit, simplified diagram.

Part II.

METHODS AND MEANS.

The foregoing section has dealt with the more or less general aspect of modern transmission maintenance. The economic justification for good maintenance has been emphasized and the general lines upon which such maintenance is to-day provided for have been indicated. The present section deals particularly with the various factors affecting transmission efficiency in the various portions of the plant, and the methods and means for measuring the influence of these.

The last few years have seen considerable advances in the development of precision sets for telephone transmission measurement, and it is proposed to refer here to the application of such sets to the maintenance problem, in order that telephone engineers may better realize the ease with which such measurements can now be made.

Experience of the last decade in measurements of this kind has culminated in the development of precision measuring sets in such forms that they can be

Telephone transmission efficiency can be defined in terms of "intelligibility," or the ability of a system (the word system as used here comprises the items of telephone plant in service during a conversation between two subscribers) to transmit ideas correctly. Intelligibility can, in turn, be expressed in terms of "articulation," which can be defined as the ability of the system correctly to transmit sounds.

The chief factors determining the transmission efficiency of a system are shown diagrammatically in Fig. 5, which has been drawn up with particular reference to the viewpoint of transmission maintenance. Definitions for the less well-known terms used are given in this figure.

The five factors determining articulation, and therefore transmission efficiency, are :—

(A) Non-linear distortion.
(B) Noise conditions.
(C) Cross-talk.
(D) Echoes and transient effects.
(E) Frequency response.

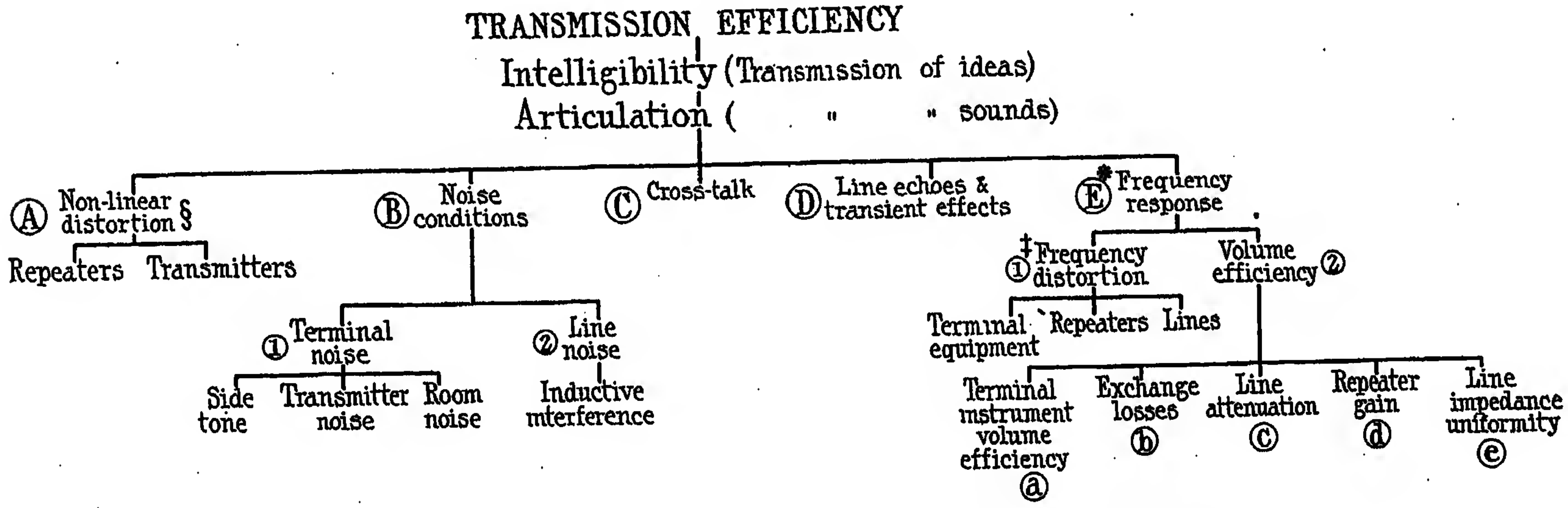

FIG. 5.—Diagram showing factors affecting transmission efficiency.

* The frequency response of a system is defined by its attenuation/frequency characteristic.
‡ The frequency distortion of a system is the distortion due to unequal attenuation of the different frequencies.
§ Non-linear distortion is caused by the output energy of a system not being directly proportional to the input energy, and results in the production of overtones not present in the original wave.

operated reliably by the more skilled members of the regular maintenance staff. By the use of such instruments the very considerable economy resulting from good transmission maintenance can be realized.

A number of the instruments described in this paper differ to some degree as to precision, range and portability. For the sake of identification and ready reference, type numbers have been used throughout in the description of the instruments.

In proceeding to a description of the various measuring sets, it is well to review some of the essentially theoretical aspects of the subject. So far, only the more practical aspects have been dealt with.

As the transmission efficiency of any portion of the telephone plant depends upon a large number of factors, it is well here to consider these in their relation to one another, as this will, of course, determine the care and cost which can justifiably be expended in maintenance tests upon each.

(A) NON-LINEAR DISTORTION.

Non-linear or asymmetric distortion is the least important of these. It occurs chiefly in repeaters and in transmitters when these are handling energy in excess of the value for which they have been designed.

In the case of repeaters it may be brought about if, by the imperfect control of repeater gains upon a long line, the power handled by a vacuum tube in the repeater is greater than it should be. In practice this is guarded against by a proper observation at each repeater station of the "transmission level," or in other words the voltage upon the circuit.

In the case of ordinary transmitters, non-linear distortion is greatly increased during loud speaking or shouting, particularly when this is close to the instrument.

The next two factors influencing transmission efficiency, namely, noise conditions and frequency response, are interdependent in that it is the difference between

the volume of reproduced speech and the volume of noise present which influences the articulation.

Both these factors are therefore of great importance.

(B) Noise Conditions.

The study of the influence of noise conditions upon transmission efficiency has only of recent years received

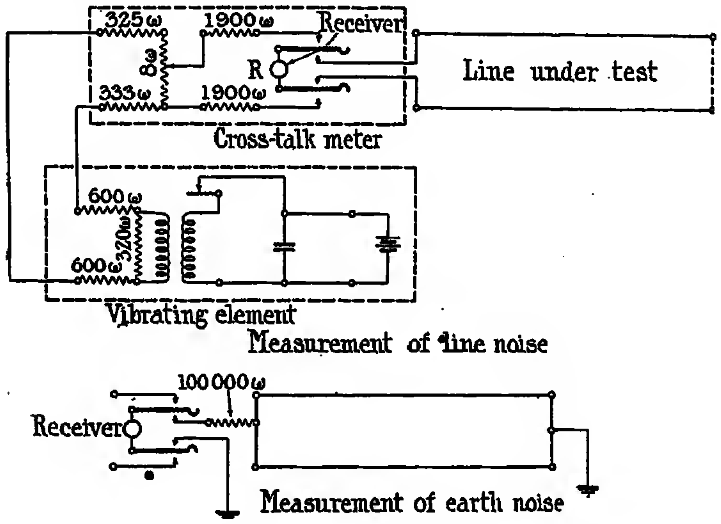

Fig. 6.—Circuit of noise-measuring set.

the attention which it deserves, and, although modern plant is now planned and constructed taking full account of the noise conditions to which the system might be subjected, it is necessary to be on the alert lest the increase in the noise condition of the circuits reaches such values that the transmission efficiency is impaired to an appreciable extent.

(1) *Terminal noise.*—This calls for little comment. Its presence at the sending end is due to the side tone of the terminal instrument, which is determined by the design of the latter and is therefore not likely to vary from time to time. Should it happen that under conditions of repair an incorrect connection is made within the set, leading to excessive side tone, this should be immediately observed and therefore corrected at once. Terminal noise is due chiefly to room noise which, except to the degree that its effects are worse when side tone is excessive, can obviously only be diminished by the subscriber. The most serious effect of room noise is due to side tone when receiving; it can be reduced by covering the transmitter mouthpiece with the hand. When subscribers' sets of the anti-side tone type are used, the effects of room noise are avoided. In cases where the transmitters employed are of a type unsuited to the circuits in which they are used, terminal noise may be caused by transmitter burning.

(2) *Line noise.*

(*a*) *Inductive interference.*—Line noise is generally due to inductive interference from external power circuits.

The important part which noise plays in determining the transmission efficiency of an average commercial telephone connection can be realized from the following example, based on known data regarding the influence of noise and other factors upon intelligibility.

Assuming a connection under average plant conditions between two subscribers each provided with central battery sets on 1-mile loops (20-lb. conductor) and connected by aerial lines equivalent to 30 miles of standard cable, the average line noise present upon such a connection is responsible for a decrease in intelligibility equivalent to the decrease in intelligibility which would be caused by increasing the equivalent cable length to about 45 miles, with the circuit absolutely quiet. (The increase in distortion with an increase in equivalent cable length has here been neglected.)

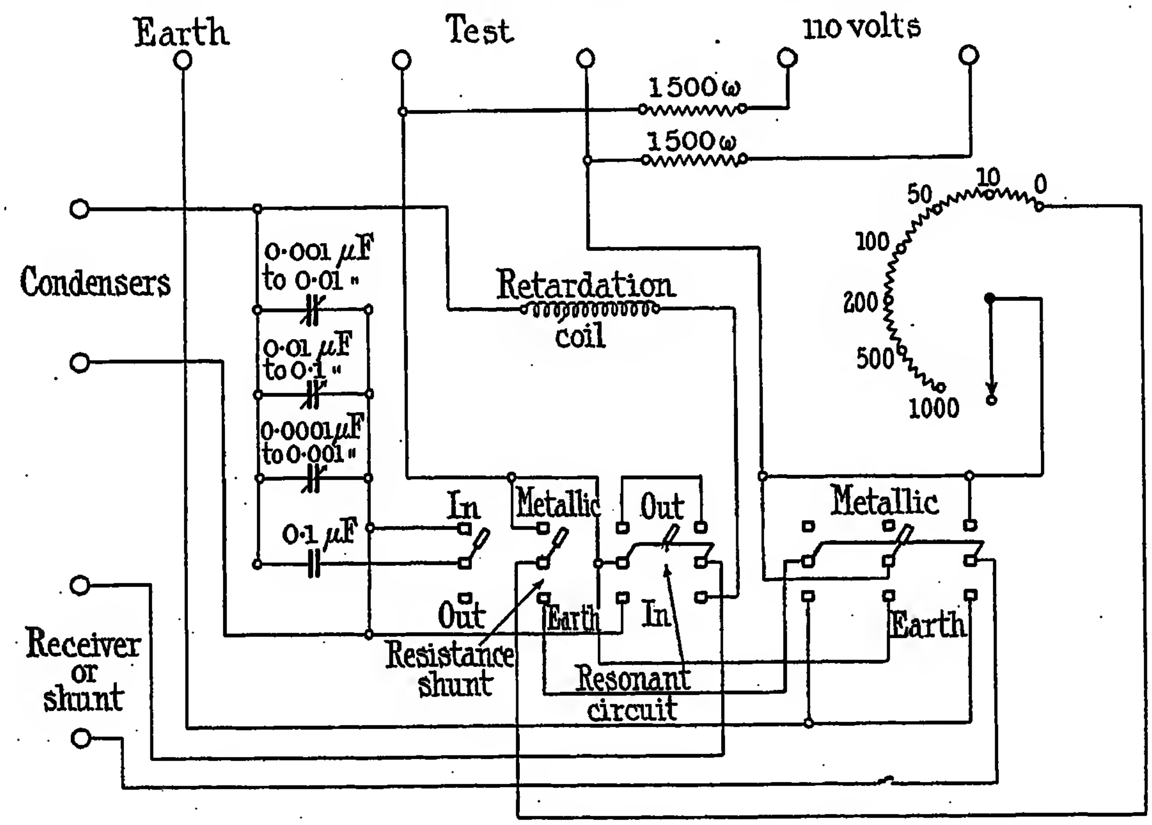

Fig. 7.—Circuit of "2-A" noise-analysing set.

The noise upon any circuit can be directly measured by means of a "1-A noise-measuring set" in terms

of an arbitrary noise unit. The effect upon transmission efficiency of various amounts of noise has been closely studied, so that an estimate can now be made of the reduction in intelligibility in any given case due to the presence of a given amount of noise.

The circuit of the noise-measuring set referred to above is illustrated in Fig. 6. It is a portable instru- calibrated to read in millionths of the output current from the source.

The circuit arrangements used for noise measurements are shown in Fig. 6. In measuring noise to earth, the two wires of a circuit within the cable under test (being subjected to the inducing influence) are connected to earth through a high resistance in series with the noise-

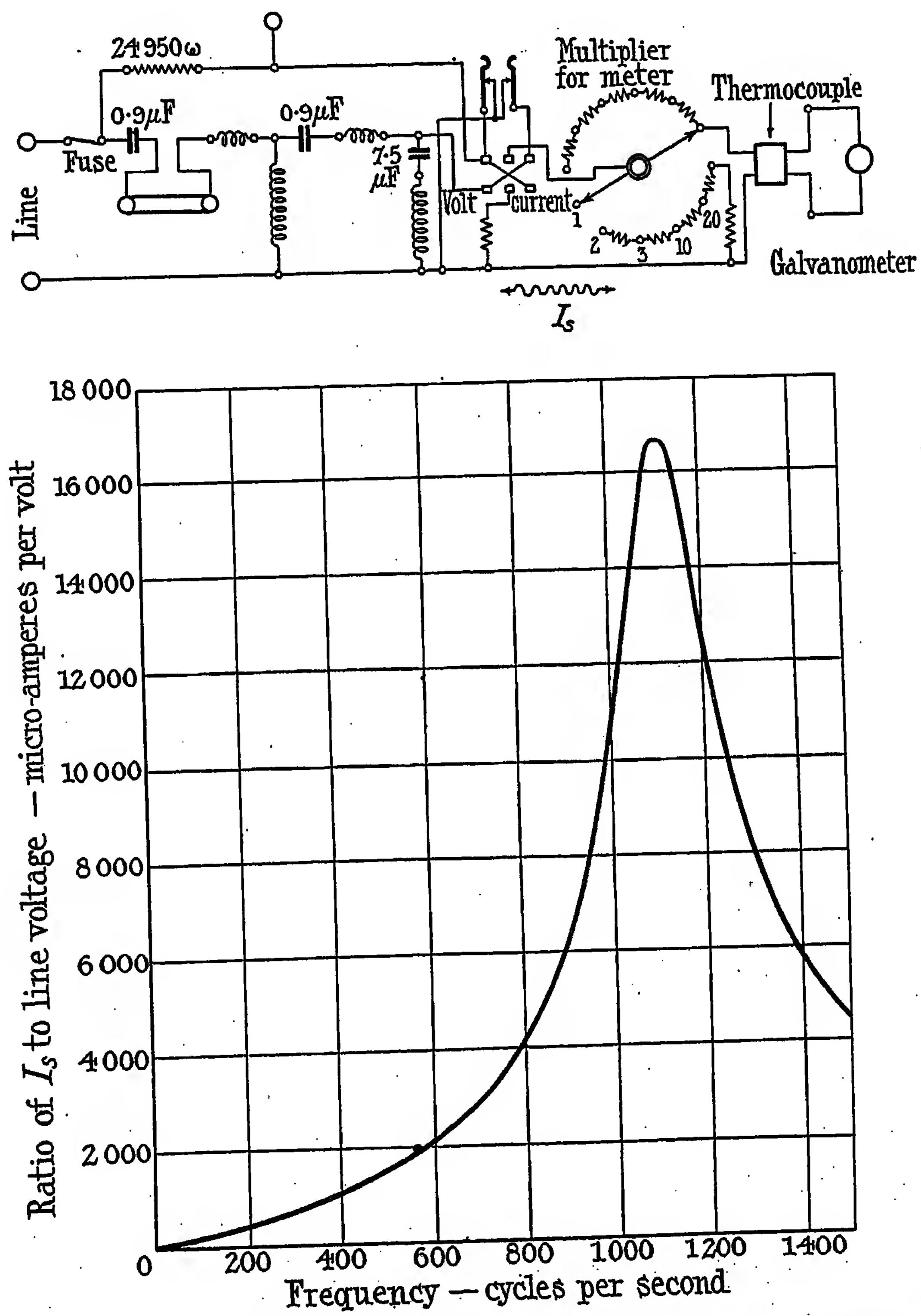

FIG. 8.—Circuit and calibration curve of telephone interference-factor measuring set.

ment including a standardized vibrating element or noise standard generating a noise of comparatively low fundamental tone very rich in harmonics. It is used in conjunction with a potentiometer, the noise upon the circuit under test being observed in a receiver and measured by adjusting the potentiometer setting until the noise in the receiver, when connected alternately to line and standard, is judged to cause the same interference with conversation. The potentiometer scale is measuring receiver and the noise units present in the receiver measured by comparison with the noise standard. This quantity can be regarded as a measure of the voltage to earth induced by the disturbing influences and tending to cause noise upon the circuit due to unbalances.

The number of noise units present in the receiver when connected across the two lines of the circuit is then measured. This quantity can be regarded as a

measure of the noise induced upon the circuit. The ratio of the noise to earth to the noise in the metallic circuit so measured may be taken as a rough index of the balance to earth of the cable under test from the viewpoint of freedom from inductive interference.

Two further instruments used in connection with noise investigations may be mentioned here.

The 2-*A noise-analysing set*, the circuit for which is shown in Fig. 7, is used for determining the frequencies of the different overtones present in a noise and, in conjunction with the 1-A noise-measuring set, may be used for obtaining an approximate estimate of the relative magnitudes of the different overtones.

The *telephone interference factor meter*, the circuit for between telephone circuits in millionths of the current which flows from a standard talking set into a universal shunt having about the same impedance as a long non-loaded open-wire circuit, say about 600 ohms.

The fundamental criterion of cross-talk between two circuits is the amount of the energy transferred from a sending end of one circuit to the receiving end of another and, as it may happen that the characteristic impedances of these circuits are different, it is necessary that this fact should be allowed for in measuring cross-talk.

In most cases it is necessary to make allowance for this fact in correcting cross-talk readings as actually made with a measuring set by multiplying by a factor $\sqrt{(z_2/z_1)}$, where z_1 and z_2 are the characteristic impedances of the disturbing circuit and the disturbed circuit respectively.

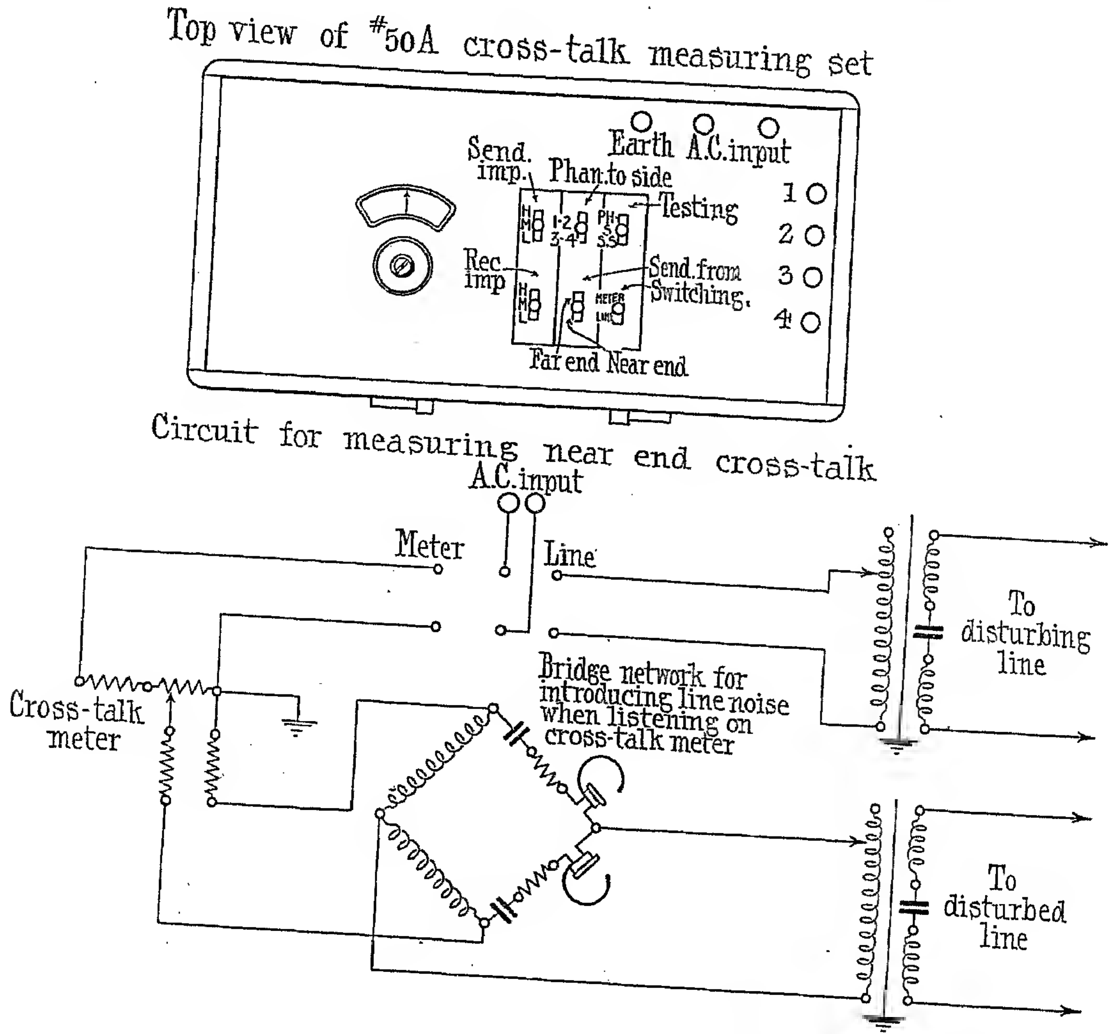

FIG. 9.

which is shown in Fig. 8, is used to measure the telephone interference factor of the wave-form of any electrical machine or system, this factor being an approximate measure of the relative tendency which the electrical plant involved will have to cause noise in a telephone circuit, other conditions remaining constant.

These two instruments are used in association with investigational work rather than with regular transmission maintenance, and do not therefore call for more detailed description.

(C) Cross-talk.

The ordinary methods for the measurement of cross-talk upon a circuit by means of a cross-talk meter are now well known to telephone engineers. Until recently it was found convenient to express the cross-talk

In making cross-talk measurements upon noisy lines, difficulty is experienced in obtaining a good balance between the cross-talk current in the testing receiver when connected alternately to the disturbed line under test and to the cross-talk meter. This practical difficulty is eliminated in the cross-talk measuring set indicated in Fig. 9 in which two balanced receiving circuits are used to connect together the receivers, the "listen" terminals of the cross-talk meter and the disturbed line, in such a manner that the line noise will be heard at all times in the receivers while the presence of the disturbed line will not affect the current flowing into the receivers from the cross-talk meter, and vice versa. This is, of course, an application of the Wheatstone bridge principle.

This set is arranged to measure the current in the disturbed circuit in millionths of the current passing in the receiving circuit, assuming that these circuits are of the same impedance. It is, of course, important in making such tests that the circuits under test are terminated with impedances of the same order as those of the circuits. In the cross-talk measuring set referred to, the circuit under test can be terminated by impedances approximately corresponding to 1 800, 1 200 or 600 ohms, repeating coils (transformers) with variable ratios of transformation obtained by means of tapping being employed. These values have been chosen to cover the range of normal impedance values occurring in a modern telephone system, namely, "heavy" loaded, "medium" loaded and non-loaded cable circuits.

A balanced retardation coil is provided in the testing circuit to enable cross-talk tests to be made between the phantom and side circuits of a group of four wires.

For the termination of the distant ends of the circuit under test it is usual to employ a resistance box, from which resistance values corresponding to the three

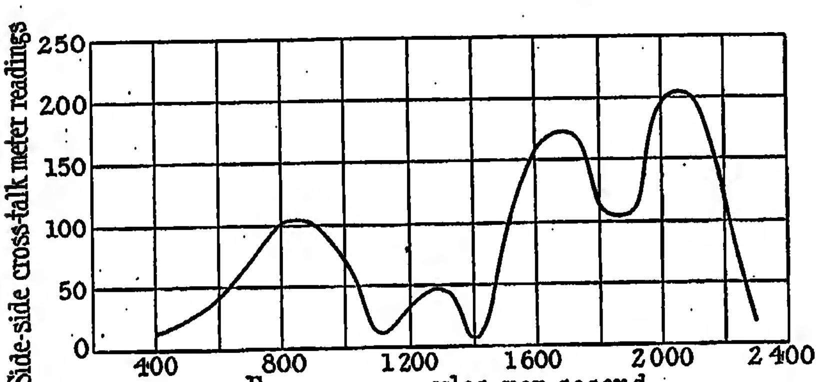

FIG. 10.—Curve showing variation of cross-talk with frequency.

From tests made on a quad of 1·0 mm conductors in cable, 22·2 km long, loaded every 2 km with 0·177-henry coils in the side circuits and 0·107-henry coils in the phantom side. The far end was terminated with pure resistance equal to the characteristic impedance.

impedances given above can be obtained. For convenience of making phantom circuit to side circuit measurements, the resistances for terminating the side circuits are of the balanced type, the mid-points being used for taking off the phantom taps.

It is, of course, of vital importance that cross-talk measuring apparatus such as that described above is carefully balanced and itself free from cross-talk.

In making cross-talk tests upon circuits, it is important that a source of testing current be employed which gives results comparable with those obtained if actual speech were employed.

When cross-talk frequency curves are obtained from measurements on loaded cable circuits, it is frequently found that these are not smooth and regular but are of an undulatory nature. Fig. 10 shows a typical curve of this kind. The undulations may be due to a variety of causes, one of which, and probably the most important, being that the cross-talk as measured is the summed-up effect of a number of sources of cross-talk which combine in different ways, depending upon the frequency. If there are two sources of cross-talk not close together and the cross-talk due to each as measured at the end of the line is known, the two values must be combined at an angle, depending on the frequency, to obtain the total cross-talk. The cross-talk due to each source alone varies approximately as the frequency, but that due to two sources may vary more rapidly, owing to the variation of the angle between them.

From the above, it is evident that since a small change in value of a single frequency might cause a change from a high to a low value of cross-talk, single-frequency cross-talk tests cannot in general be relied upon to give an indication of the cross-talk condition of the plant.

A source of power has been developed which gives results comparable with those of speech. It consists of an electrically driven vibrator, giving a low-frequency tone rich in harmonics. In using this source of power for cross-talk measurement or loaded circuits, a network is inserted in the circuit to limit the current passing and to terminate properly the sending circuit.

(D) Line Echoes and Transient Effects.

These effects are inherent in long-distance circuits involving loading and repeaters, and are taken into account in the design and planning of such circuits. They are dependent on the type of loading employed and the number and location of the repeaters, also upon the transmission gains at which the repeaters are operated and the degree of unbalance between balancing networks and lines. If under service conditions these effects are found to be appreciable, they must be diminished by a reduction of repeater gains or by an improvement in the degree of balance between lines and balancing networks.

The instruments used for the measurement of repeater gain and line impedance balance are referred to later.

(E) Frequency Response Characteristic.

The last of the five chief factors determining the transmission efficiency of the system remains to be dealt with.

This factor has been referred to earlier as the frequency response characteristic of the system, and involves the volume transmission efficiency of the system for all individual frequencies occurring in the sounds which it is desired to transmit.

The frequency response characteristic of a system is usually represented by a curve plotted between response (vertically) and frequency (horizontally), the values of response being in terms of the total attenuation occurring in the system at each individual frequency.

It will be seen from Fig. 5 that the influence of frequency response upon the transmission efficiency can be regarded as due to two separate considerations, namely, frequency distortion and volume efficiency.

(1) *Frequency distortion* is, of course, the distortion due to various single frequencies in the telephone range being attenuated differently. The term "volvme efficiency," as used here, involves the idea not of the volume efficiency at one frequency but the effective volume efficiency due to all the frequencies being transmitted, the volume efficiency for each individual frequency being weighted in accordance with its importance.

Dealing first with the frequency distortion factor for the system, this will depend on the frequency distortion occurring in the terminal equipment, comprising the telephone instruments and the exchange equipment, the frequency distortion in the lines themselves and also in the repeater. The frequency distortion occurring in the terminal equipment and in the lines is determined at the time the system is planned and constructed.

In the case of repeaters of the 2-wire type, the frequency distortion present may vary from time to time, depending upon the margin existing between the gain at which the repeater is operating and the singing point between the lines and balancing networks between which the repeater is working. Ordinarily, repeaters of this type are so designed and adjusted that the gains given at various frequencies are those required when the lines and networks with which they are used are balanced for impedance within certain well-defined limits. Should it happen that, owing to line troubles, the standard of impedance balance between the line and network is lowered, and that at the same time the repeater gain is not reduced by a corresponding amount, the gain given by the repeater at different frequencies will depart from the normal values.

This effect is well illustrated by Fig. 11, which shows the transmission frequency characteristic of a repeatered loaded cable circuit under two conditions: first, when the gain given by the repeater almost brings the system to a singing condition; and, secondly, when the repeater gain has been lowered from its previous value by about 4 miles of standard cable.

It is evident, therefore, that the varying effect of frequency distortion in repeaters of the 2-wire type will have to be guarded against by ensuring that line-impedance uniformity is maintained to a certain standard, and that repeater gains are maintained uniform at certain predetermined values.

Considerations of volume efficiency for the system demand the same requirements, and the means which are employed for the maintenance of these conditions are dealt with below under "Volume Efficiency."

It is necessary to point out here that in the case of repeaters of the 4-wire type the above considerations do not apply, as the gain which such repeaters can give is not so dependent on the impedance balance of the lines to which they are connected.

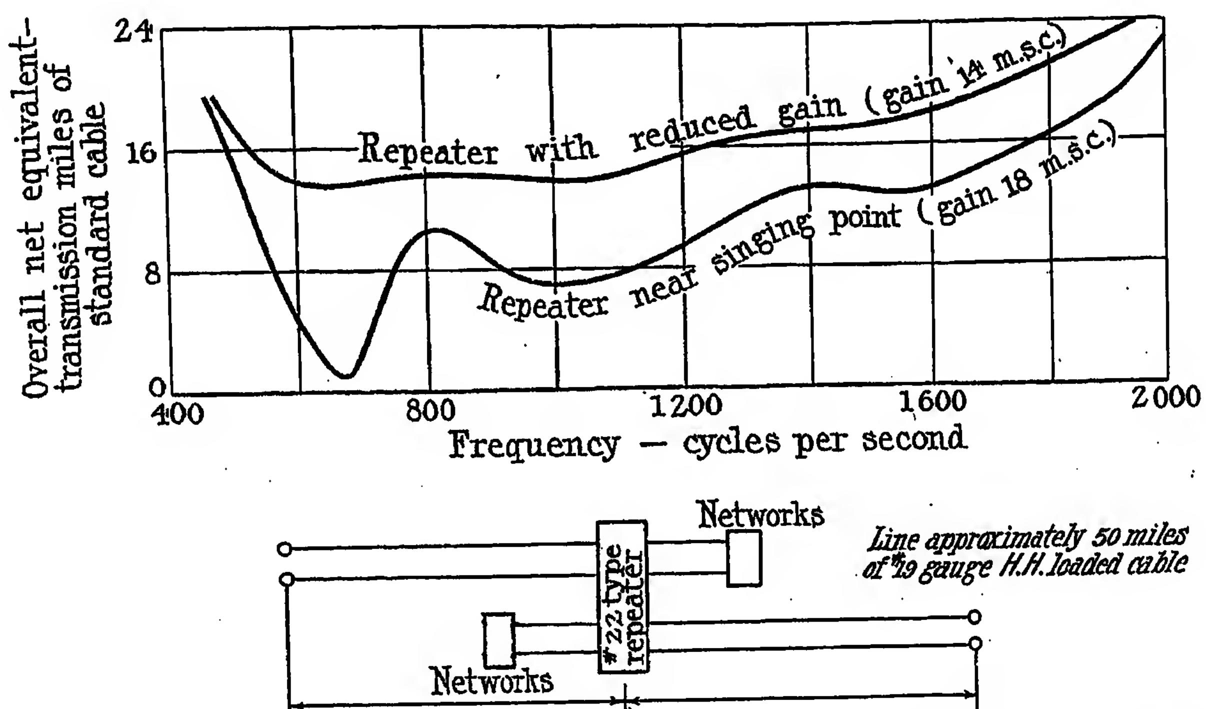

FIG. 11.—" 22 " type repeaters. Effect of lowered line singing point upon attenuation characteristic of circuit.

(2) Volume Efficiency.

We turn now to the second factor contributing to the frequency response characteristic of the system, namely, volume efficiency. From the viewpoint of transmission maintenance, this is without doubt the most important of any single factor bearing upon transmission efficiency. In the early days of telephone transmission engineering it was the only factor to which serious attention was given by engineers, and a tendency remains to-day in some countries to judge the transmission efficiency of a system from the attenuation values of its component parts, with entire disregard of noise condition, or even of distortion.

The volume efficiency of a system depends upon the volume efficiency of the component parts, terminal equipment lines and repeaters, etc., at all frequencies. It also depends upon the transition losses, which are liable to occur at the junction between the various plant items.

Of these various factors, all, with the exception of transition losses, are controlled by routine transmission maintenance. Ordinarily, in planning the system, care is taken that the impedances of the various circuit elements, which are or might be used in conjunction one with the other, are sufficiently similar in impedance characteristics to cause inappreciable losses. In the matching of the impedance values of various parts of the plant, repeating coils and transformers with "inequality ratio" windings play an important part, and it is, of course, important in new construction or

in extension work that transformers of the proper impedance ratio should always be employed.

The remaining factors, as will be seen from Fig. 5, are resolved into the following items :—

(a) Terminal-instrument volume efficiency.
(b) Exchange losses.
(c) Line attenuation.
(d) Repeater gain.
(e) Line impedance uniformity.

The means and methods available for the measurement of these items will now be described.

(a) *Terminal-instrument volume efficiency.*—Until recently it has been almost general practice with telephone administrations to assume that a telephone set when once put into service retains its original efficiency. In cases where obvious defects have arisen in subscribers' sets, it has been left to the regular maintenance staff to effect such repairs as were clearly necessary, without an accurate check on the efficiency of the telephone set being made. Undoubtedly the explanation of this has been the difficulty and cost of making efficiency tests, due to the necessity of making actual speech tests under more or less laboratory conditions, the volume efficiency of the instrument under test being carefully compared with standard instruments of known efficiency.

The institution of repair and recovery workshops, where defective instruments are corrected by a specially trained staff, and the development of rapid routine methods for making volume efficiency tests, have overcome this difficulty.

(b) *Exchange losses.*—In the earlier part of this paper (page 659), reference was made to the necessity of providing an instrument for measuring in a rapid routine manner such parts of the exchange equipment as experience has shown to be subject to defects. Such an instrument is the 1-B transmission measuring set, the circuit of which is given in Fig. 12. It has been primarily designed for measuring with a 1 000-cycle alternating current the transmission losses caused by telephone apparatus and exchange equipment under regular operating conditions. It can also be used for measuring the loss in junction, trunk lines, etc., provided that the two ends of the circuit or equipment to be tested can be made available at the testing point. The set is arranged to measure losses from 0 to 46 miles of standard cable in steps of half a mile. It is constructed in a portable form and weighs approximately 13 lb.

While we can use any source of single-frequency current giving suitable wave-form and approximately the correct frequency, a special single-frequency source to give current of a frequency of 1 000 cycles per second has been designed for use with the set. This oscillator consists essentially of a generator element and a filter circuit. The generating element consists of a carbon button and two specially-wound receiver spools coupled by means of a tuned metallic reed. The system operates off three dry cells, which are mounted in the same carrying case as the generating element proper.

The circuit of this measuring set is made up of two artificial line branches, which are permanently bridged together, at the end of which the alternating-current source is connected so that the same alternating potential is impressed on both branches. These two branches are similar, except that the apparatus or circuit of which the transmission loss is to be measured is connected into the upper one, while the lower one consists of an arrangement of variable resistances both in series and in shunt, constituting a variable artificial line.

In using the set, the variable artificial line in the lower branch of the circuit is adjusted so that the same volume of transmission is received over each of the two branches at the receiving ends, and the loss in the apparatus under test is known directly from the

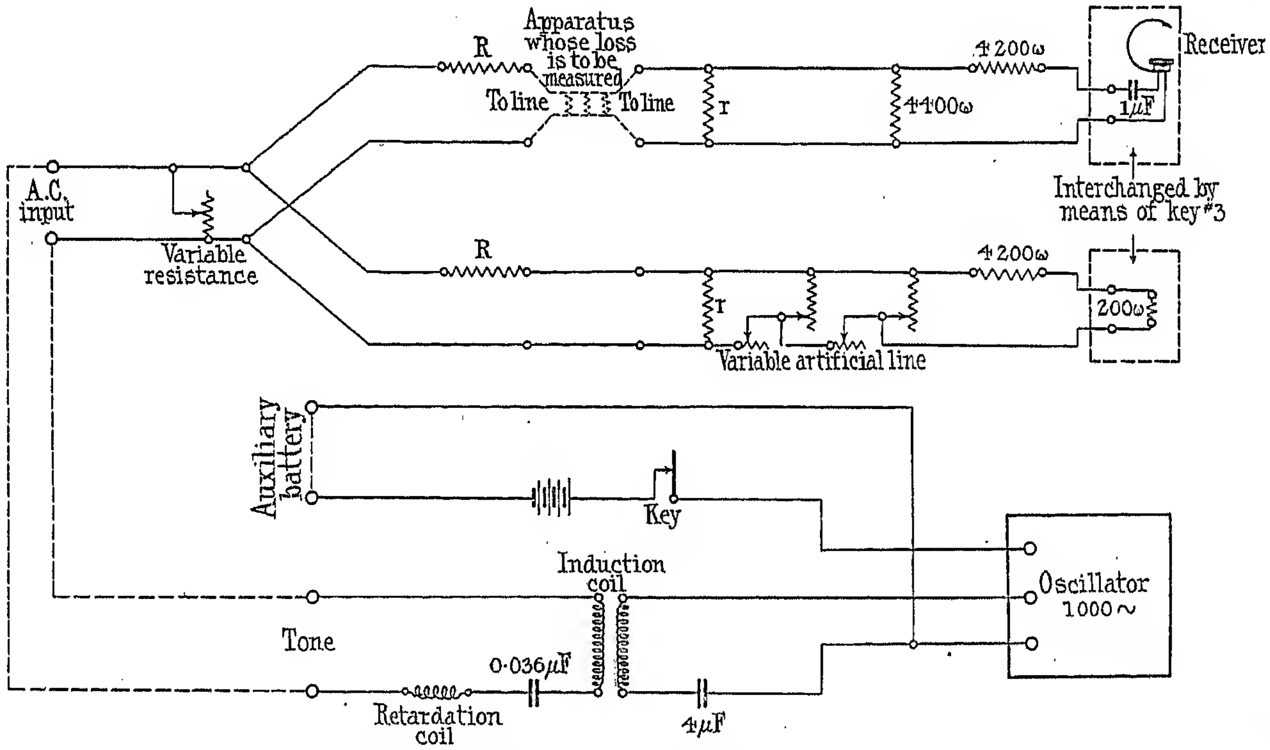

FIG. 12.—Circuit of "1-B" transmission measuring set and "2-B" oscillator.

setting of the variable artificial line, which is calibrated in miles of standard cable. A receiver and a condenser in series are connected to the receiving terminals of the upper branch of the circuit, and a 200-ohm resistance (which simulates at 1 000 cycles the impedance of the receiver and the condenser in series) to the receiving terminals of the lower branch of the circuit. Actually, of course, the receiver combination and the 200-ohm resistance are interchanged between the two branches, as is necessary for making the transmission determination by means of a switch. The artificial lines used in the two branches of the circuit are made up of non-inductive resistances.

The apparatus to be measured is connected between the two parts of the artificial lines in the upper branch. The variable artificial line in the lower branch has been designed in such a manner that, regardless of the setting, the impedance of the circuit to the right of the resistance r in the lower branch is uniform. The resistance R can, by means of a key, be made to have any one of three values corresponding respectively to heavily loaded, medium loaded, or non-loaded lines. Similarly, by suitable changes in the value of r, the artificial line made up of r in conjunction with the resistance to the right can be made to have any one of the three values mentioned. As the transmission loss caused by telephone apparatus depends upon the type of line into which it is inserted, the above-mentioned arrangement makes it practicable to determine the loss due to equipment used with various types of circuits, and thus to measure the losses under the approximate impedance conditions which hold in regular service.

(*c*) *Line attenuation.*—The transmission set described above can be used for measuring attenuation only when both ends of the line or circuit under test are available at the set. This, as has been explained earlier, involves the looping back of lines at a distant point. Apart from the obvious inconvenience of such a method, the disturbance to traffic conditions involved by the use of several lines simultaneously for testing purposes has justified the development of an instrument which in use involves only the line under test. The circuit of this instrument, the 3-A transmission measuring set, is indicated in Fig. 13. It is used for measuring the transmission equivalents of lines, and also to measure the losses in apparatus and exchange equipment, when these are desired, to a higher degree of accuracy than is possible with the 1-B set described above.

The 3-A transmission measuring set is arranged in a portable form and employs a direct-reading meter. It uses visual indication instead of audible indication. It is calibrated directly in miles of standard cable and enables transmission-equivalents from zero to 30 miles of standard cable to be accurately and quickly measured to within 0·1 standard mile. It is also arranged to permit the current supply conditions of subscribers' operator's cord circuits and switching trunks to be measured.

The dimensions of the set are 22 in. × 8 in. and its weight is about 37 lb., excluding the source of testing current. While any source of current having the proper output, suitable wave-form and frequency, can be used, a special oscillator generating a current having a frequency of 1 000 cycles per second has been designed for use with the set and is known as the " 3-A " oscillator. This oscillator delivers more power than is available from the 2-B oscillator used with the 1-B transmission measuring set.

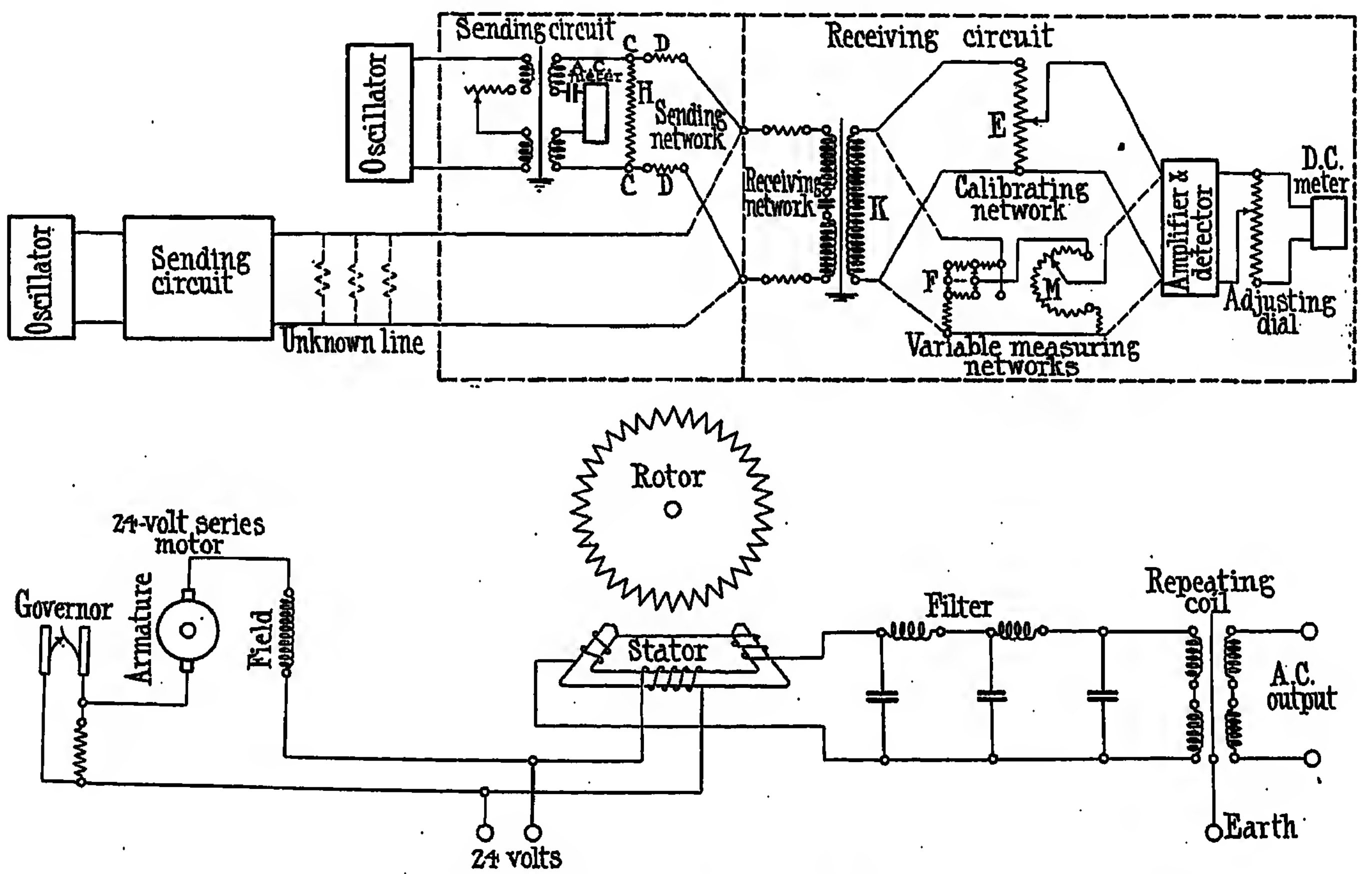

FIG. 13.—Circuit of " 3-A " transmission measuring set and " 3-A " oscillator.

Both the measuring set and its oscillator operate satisfactorily from the regular 24-volt battery as a source of power. The set contains two vacuum tubes but does not require a separate plate battery, the 24-volt battery supplying both filament and plate currents.

The operation of this set when used for measuring the attenuation of a line is briefly as follows :—

Referring to the measuring set located at the receiving end of the line under test, alternating current is passed from the sending circuit of this set into a resistance network, which approximates in impedance to the transmitting end of the line under test. This network is connected to another network (having an impedance approximating to that of the receiving end of the line under test) which forms part of the receiving circuit.

The current from the sending circuit flows through the networks referred to above, and after passing through a transformer and a calibrating network reaches an amplifier-detector, the output of which is connected to a direct-current meter upon which a deflection is produced. By means of an adjusting resistance located across this meter, the deflection is adjusted to a definite value. Such tests with the sending and receiving circuits (both at the receiving end of the line under test) connected together can be called calibration.

The sending and receiving circuits referred to above are then separated, the receiving circuit being connected by means of a switch to the receiving end of the line under test, and the sending circuit, or a similar one, to the sending end of the line. The calibration network, which during calibration caused a definite transmission loss, is now replaced by two variable measuring networks, the substitution being effected by means of switches. One of these networks is variable in small steps to cause losses from zero to 10 miles, while the other is variable in steps of 10 miles. When the line under test is connected between the sending and receiving circuits, the current which flows into the receiving circuit will, of course, be reduced to a value less than that which was obtained during calibration, on account of the attenuation of the line under test. The deflection on the meter will consequently be less than when the circuit was being calibrated. If the transmission loss caused by the variable measuring network is decreased until the deflection on the meter is the same as during calibration, the difference between the loss caused by the fixed calibrating network and that caused by the variable measuring network will be equal to the transmission loss caused by the line under test. The measuring networks are calibrated to read this difference directly.

The complete sending circuit of the set consists of an oscillator, a rheostat for regulating its output, an alternating-current meter for measuring the output, and a network of resistances which form the artificial line.

The receiving circuit consists primarily of a resistance network, a transformer K, a calibrating network E, variable measuring networks F and M, a resistance-adjusting dial, an amplifier and detector, and a direct-current meter.

In the sending circuit the resistance network includes the resistances DD, which are adjustable to have a total impedance of 600, 1 200 and 1 800 ohms respectively, corresponding to low, medium and high impedance. The resistance H is non-inductive and is connected across the terminals of the artificial line DD. It will be noted that the alternating-current milliammeter is connected in the output circuit of the oscillator so that it reads the total current flowing through the resistances DD and H. The resistance H is so low in comparison with DD that only a very small proportion of the total current flows through DD when it is connected to the line or to a receiving circuit. Therefore, with a given current through the milliammeter, it can be assumed that the voltage between the points CC is practically independent of the impedance to which the sending circuit is connected, and that if any two sending circuits have the resistances and currents adjusted to the same values, the voltages across the points CC will be equal.

In the receiving circuit the transformer K is shielded and so designed that its impedance will be approximately 600 ohms when connected to the apparatus to its right. In order that the impedance of the receiving circuit can be adjusted to the values of 600, 1 200 and 1 800 ohms corresponding to the impedance of the receiving end of the line, resistances are connected between the coil and the terminals to which the line under test is connected. The calibrating network E is a potentiometer designed so that the ratio of the voltage impressed by it on the amplifier to that impressed upon it by the transformer K corresponds to a transmission loss of 30 miles of standard cable at a frequency of 800 cycles per second. The variable measuring network M is a potentiometer having a total resistance corresponding to that of the calibrating network E, but designed so that it can be adjusted to cause losses from zero to 10 miles. It is in the form of a circular slide wire and is calibrated in steps of 0·1 mile. The variable network F is a constant-impedance shunt, so that the ratio of the current entering the variable network M, to the current entering the shunt, can be adjusted to values which correspond to transmission losses of 0, 10 and 20 miles of standard cable at 800 cycles per second. The amplifier and detector circuit contains two vacuum tubes, one serving as an amplifier and the other as a combined amplifier and rectifier or detector. The adjusting dial is a circular slide-wire potentiometer, the setting of which determines the current supplied to the direct-current meter. It is so arranged that the impedance, as looked at from the direct-current meter terminals, is constant, thus keeping constant the damping of the meter.

The various jacks and terminals enable the set to be used with different types of jacks, or with ordinary wires, and also permit the use of the set for the measurement of current-supply conditions, etc.

A still higher development in transmission measuring apparatus is the 4-A transmission measuring set. This set has been designed for use at the more important centres in the trunk line plant for making measurements over a greater range of conditions, particularly as regards frequency, than is possible with the sets already described.

The approximate overall dimensions of this set are 33 in. × 18 in. × 14 in. It is intended as a permanent fixture in important terminal stations, and is usually provided with a number of local circuits terminating on jacks for the use of the test clerk, to facilitate the measuring of a large number of circuits with a minimum of delay. Various signals and a telephone set are provided for use in conducting the tests. The circuit arrangements of this set are similar in principle to those in the 3-A set described above.

The range of measurement is, however, greater, as losses from 0 to 60 miles and gains from 0 to 20 miles of standard cable may be measured to 0·1 standard mile. The amplifier-detector provided in this set has three vacuum tubes, this number being necessary on account of the considerable range of the set.

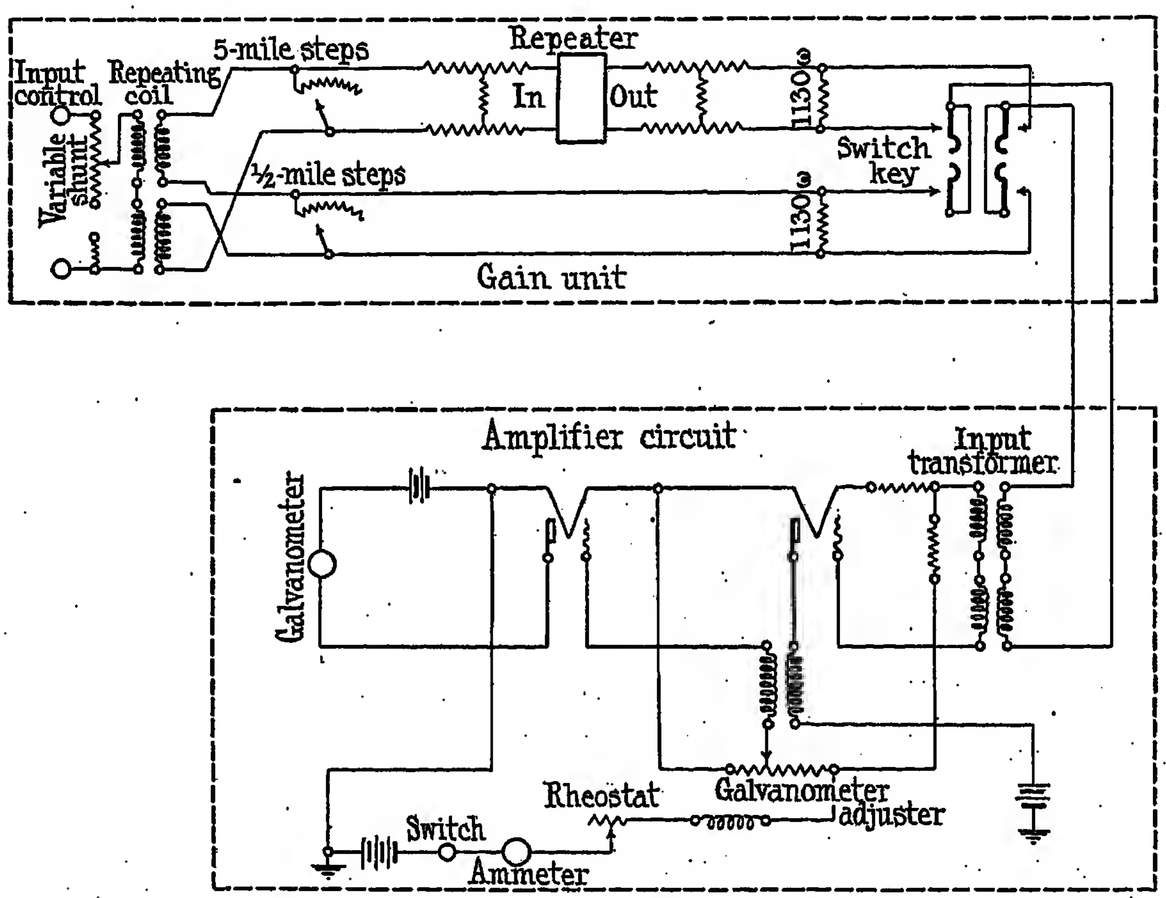

FIG. 14.—Circuit of " 2-A " repeater gain-measuring set.

While for obtaining the relation between attenuation and frequency for any line, a variable-frequency oscillator giving any single frequency between, say, 200 and 4 000 cycles is used, this measuring set is chiefly used in conjunction with a special oscillator (5-A) to make measurements at 1 000 cycles per second.

The 5-A oscillator delivers testing current the frequency of which varies rapidly to and fro over a range from 900 to 1 100 cycles per second, and experience has shown that although the true attenuation/frequency curve of the line is somewhat irregular, owing to slight impedance irregularities in line construction, the attenuation measured when this oscillator is employed is substantially that which would be obtained with a single-frequency measurement at 1 000 cycles per second, if the line construction were ideal, that is, free from all irregularities.

(d) *Repeater gain.*—In order that the gain given by any repeater (of either the 2-wire or 4-wire type) in a repeater station can be checked and calibrated for any setting of the gain control, it is usual to provide at least one repeater gain set of the No. 2 type. This gain set is mounted on two panels which are situated on the same racks as the repeaters, and is located in close proximity to jacks connecting to the various repeaters. One of the panels comprises the gain unit and the other an amplifier unit. The set is capable of measuring gains up to 46 miles of standard cable (800 cycles per second) in steps of 0·5 mile. Fig. 14 shows a simplified diagram of the circuit. Alternating current at 1 000 cycles per second is fed to the input terminals of the gain unit and passes through a repeating coil to two separate circuits, which are connected in series through the secondary windings of the repeating coil so that the same current flows into each. A variable shunt is connected across the input terminals of this coil to enable the input current to be adjusted. The two separate circuits join together again at the switch-key.

Following the upper circuit in the gain unit, the current passes through an artificial line, shunted by a variable resistance controlled by a dial switch and designed to give a series of losses in steps of 5 standard miles. The terminals of this artificial line are connected to the input terminals of the repeater to be tested, the output terminals of which are connected to another artificial line closed with a resistance. The terminals of this resistance are connected to the switch-key.

The lower circuit in the gain unit consists simply of one resistance shunted by another variable resistance controlled by a dial switch and designed to give losses in steps of 0·5 mile. The terminals of this resistance are also connected to the switch-key.

The amplifier circuit, which is shown in the lower

part of Fig. 14, comprises two vacuum tubes, the first of which acts as an amplifier and the second as a detector, in the plate circuit of which is connected a galvanometer. The switch-key is connected to the amplifier valve through an input transformer. The sensitivity of the set is adjusted by varying the grid potential of the rectifier by means of a sliding contact on a resistance connected across the filament of the first tube. The switch-key connects the input of the amplifier to either the upper or lower circuits of the gain unit.

In making the test the repeater is connected in the upper circuit of the gain unit, and the two variable shunts are adjusted until the same reading is obtained upon the galvanometer for either position of the switch-key. It is obvious that under this condition the voltages developed at the end of both the upper and lower circuits of the gain unit are equal, and, since the currents which enter these two circuits are the same, it follows that the gain given by the repeater must be equal to the difference between the losses caused by the shunts in the two circuits, neglecting for the moment the losses occurring in the two artificial lines and the transition losses which may occur at the repeater terminals, due to the impedance values of the artificial lines and the repeater not matching exactly.

Actually account is taken of the latter losses in calibration. A panel-mounted single-frequency oscillator, including two vacuum tubes, is usually provided at repeater stations for use with the above set.

The circuit of a repeater gain-measuring set in a portable form is shown in Fig. 15. This is the 3-A repeater gain-measuring set, which can be used also for the measurement of transmission losses. Its range is from 0 to 90 miles of standard cable (800 cycles per second) in steps of 0·2 mile. The set is contained in an oak case approximately $9\frac{5}{8}$ in. × $6\frac{1}{4}$ in. × 24 in. and weighs about 33 lb.

The repeater of which the gain is to be measured is connected to the set, the input of the repeater being connected to the " In " terminals of the set, and the output being connected to the " Out " terminals. The " Input " and " Output Impedance " dials are set to the required values, seven impedances (300, 700, 890, 1 130, 1 420, 1 800 and 2 280 ohms respectively) being available. These impedances should be set to approximate to the impedances of the lines on which the repeater is designed to work. The " Gain and Loss " key is put in the " Gain " position, and the " Meter-Receiver " key is put in the " Meter " position. The resistances A and B are adjusted until the output currents of each circuit branch are equal. This equality is determined by means of a thermo-couple and galvanometer in a circuit arrangement having an impedance of 1 130 ohms. The operation of the " Test " key closes one circuit branch through the thermo-couple and at the same time connects a resistance of 1 130 ohms across the other circuit branch. When no change in the deflection of the micro-ammeter is caused by the operation of the test key, the readings of dials A and B give the gain of the repeater in miles of standard cable.

The set may be used to measure the transmission loss in a piece of apparatus by connecting the apparatus between the " In " and " Out " terminals, the " Gain and Loss " key being set at " Loss." In general, the energy output from each branch of the circuit will be insufficient to operate the thermo-couple when the set is used in this way. A receiver is therefore employed to balance the set and is connected to the terminals marked " Receiver," the " Meter-Receiver " key being in the " Receiver " position.

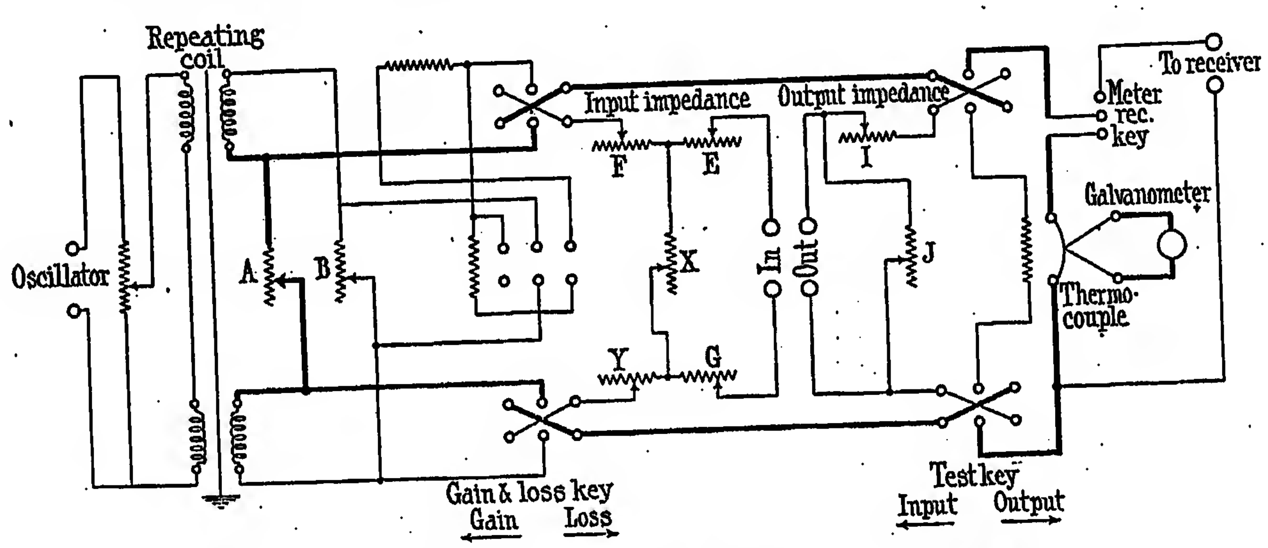

FIG. 15.—Circuit of " 3-A " repeater gain-measuring set.

With both the above sets an oscillator capable of giving power at any single individual frequency between, say, 200 cycles and 3 000 cycles can be employed. An oscillator of this type (the 4-B oscillator) is referred to later.

(*e*) *Line impedance uniformity.*—The gain at which 2-wire repeaters can be satisfactorily operated depends to a large extent upon the degree of balance existing at all essential frequencies between the impedance of the line and the balancing network associated with it.

While the 21-test already described enables the determination of the " singing point " of a line against its balancing network at the particular frequency at which the impedance unbalance is a maximum, it is sometimes necessary to know the " singing point " at a number of frequencies in order that the nature of the cause of the unbalance may be located. This information can

be quickly obtained by means of the 2-A impedance unbalance measuring set.

The impedance unbalance measuring set is a device for the direct measurement of the "singing point" at any desired frequency. Fig. 16 is a diagram of the apparatus, showing the essential parts of the circuit but omitting certain details which are of minor importance in its operation. The heavy lines show the conductors used when making unbalance measurements. The set works on a null system in which a current depending upon the quantity being measured is balanced through a galvanometer against another current from the same source which flows in a reference circuit. This eliminates errors due to fluctuations in the output of the source.

Alternating current from an oscillator is applied through a transformer A to the two resistances B and C in series. The resistance B can be regarded as a 1 200-ohm line supplying the measuring circuit, which begins at its terminals. Current from B passes to the 2-5 winding of the 3-winding transformer D, of which the line and network terminals are connected through the contacts of certain keys to the line and network terminals of the set and thence to the impedances under test. From the bridge terminals the unbalance current passes through an insulating transformer E to the adjustable artificial line F and to the potentiometer G. The voltage-drop in G is applied to the high-impedance input circuit of a 2-stage vacuum-tube amplifier. The alternating voltage in the output circuit of the amplifier is applied to the measuring rectifier and the resistance H in series, giving rise to a unidirectional current flowing in the direction indicated by the arrow. The condenser in parallel with H smooths out the current and increases the efficiency of the rectifier circuit.

The alternating voltage across the resistance C is applied through the transformer J to the resistance I and the reference rectifier in series, giving a unidirectional current in the direction shown by the arrow. The voltage-drops in the resistances H and I are opposed through the galvanometer, which stands at zero when the two currents are equal.

After connecting up, the first step in measuring a "singing point" is to calibrate the apparatus. This is done by using the reference key K which substitutes the resistances L and M for the impedances under test. These resistances are so proportioned as to give a loss of 6·4 miles through the 3-winding transformer (in addition to the copper and iron losses of 0·6 mile) without disturbing its impedance relations with the rest of the apparatus. The measuring dials of the artificial line F are turned to zero—this introduces the maximum loss—and the adjustment dial of the potentiometer G is turned until the pointer of the galvanometer stands on zero.

Restoring the reference key K to its normal position reconnects the impedances under test and reduces the unbalance current. The galvanometer is restored to balance by turning the measuring dials of the artificial line F, which reduces the loss in F and indicates this reduction by the position of the pointers on the dials. The reading of the dials is then the loss through the 3-winding transformer, less the 7 miles (6·4 + 0·6) previously existing, which is the singing point of the two impedances.

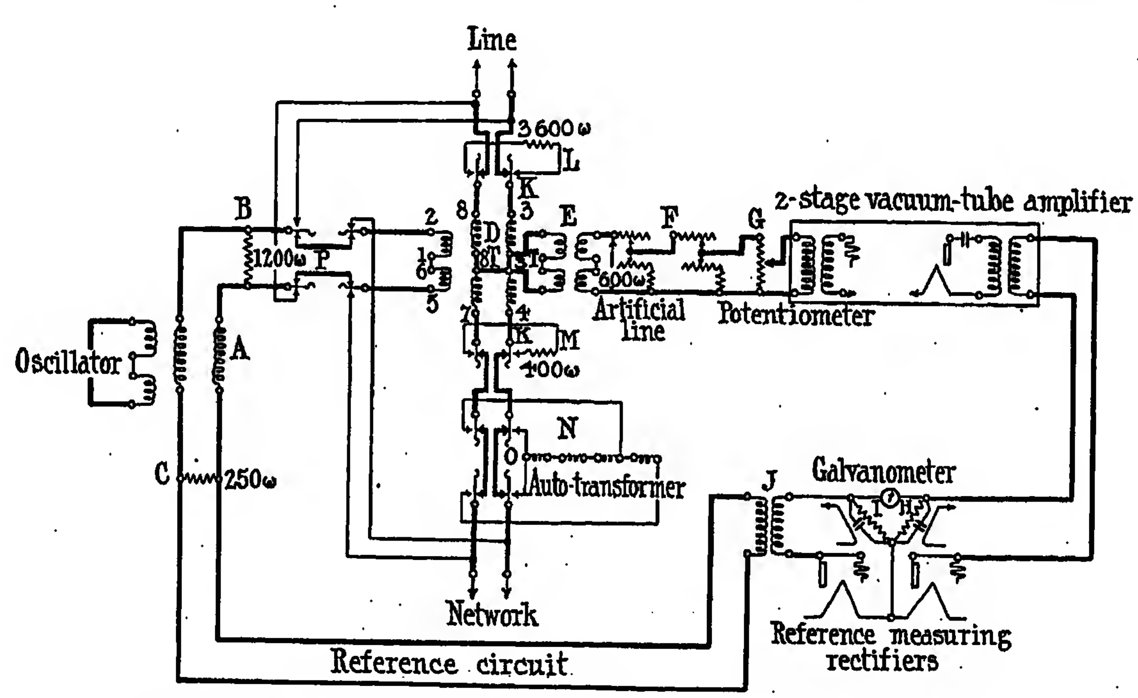

FIG. 16.—Diagram of "2-A" impedance unbalance measuring set.

Having once calibrated the apparatus at some such frequency as 1 000 cycles, the whole frequency range can be covered by successive settings of the oscillator and measuring dials without further calibration.

This set can also be used for the location of line impedance irregularities, although this operation can be more directly and simply determined by the use of the line impedance bridge.

The circuit of the 1-B line impedance bridge illustrated in Fig. 17 is intended primarily for measuring the impedance of telephone lines over a range of frequencies for the purpose of locating line irregularities. It can also be used to measure the impedance of appara-

tus. It consists of a Wheatstone bridge network made up of two ratio arms of fixed resistance, a variable resistance, a fixed inductance and a variable inductance. By means of keys, the inductance may be switched to either arm of the bridge, so as to be either in series

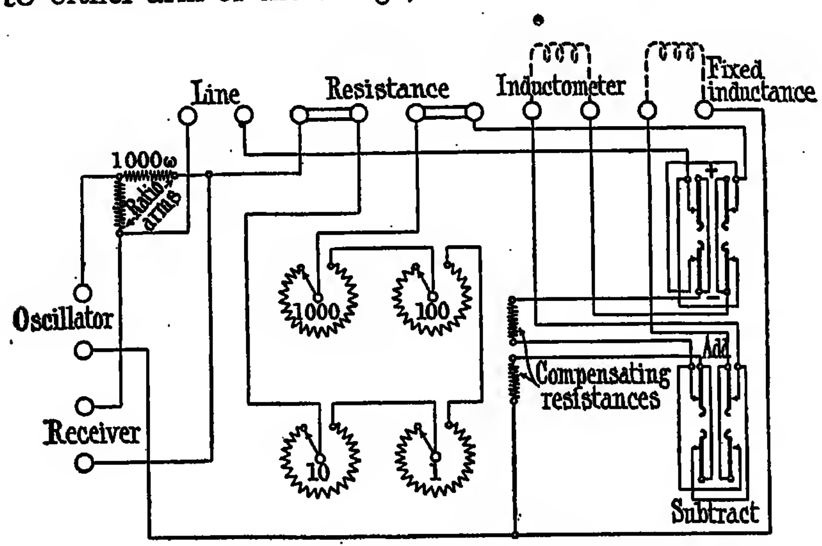

FIG. 17.—Circuit of "1-B" line impedance bridge.

with the line under test or in the opposite arm. Resistances are provided in the circuit to compensate for the effective resistance of the inductometer and the inductance coil, so that the variable resistance can be read directly to obtain the resistance component of the impedance. Detection is effected by means of a head

conjunction with several of the measuring and testing sets described above. It is designed to furnish alternating current of pure wave-form over a range of from 100 to 5 000 cycles per second by steps of 20 cycles per second and with an accuracy of 0·1 per cent.

It comprises an oscillation tube, two amplifying tubes and an adjustable resonant control circuit. The frequency is adjusted by varying the capacity and inductance of this circuit, which is associated with the oscillation tube. A number of features essential in an instrument intended for accurate measurements are secured by circuit arrangements which result in low amplitude of oscillation in the first tube. The frequency of oscillation is made relatively independent of the tube characteristics, so that recalibration is not necessary if tubes are replaced. The frequency, also, is independent of small changes in filament current and plate voltage, and is quite independent of the power being delivered from the output terminals.

The output of the oscillator is controlled by means of a potentiometer connected in the circuit between the two amplifying tubes. The power supply required by this oscillator is 1·0 ampere at 24 volts, and 0·05 ampere at 130 volts. A rheostat and meter are provided for adjusting the filament current.

The oscillator is reasonably portable, being mounted in a box with carrying handles and having overall dimensions approximately 19 in. × 19 in. × 19 in.

It has not been possible within the limits of this

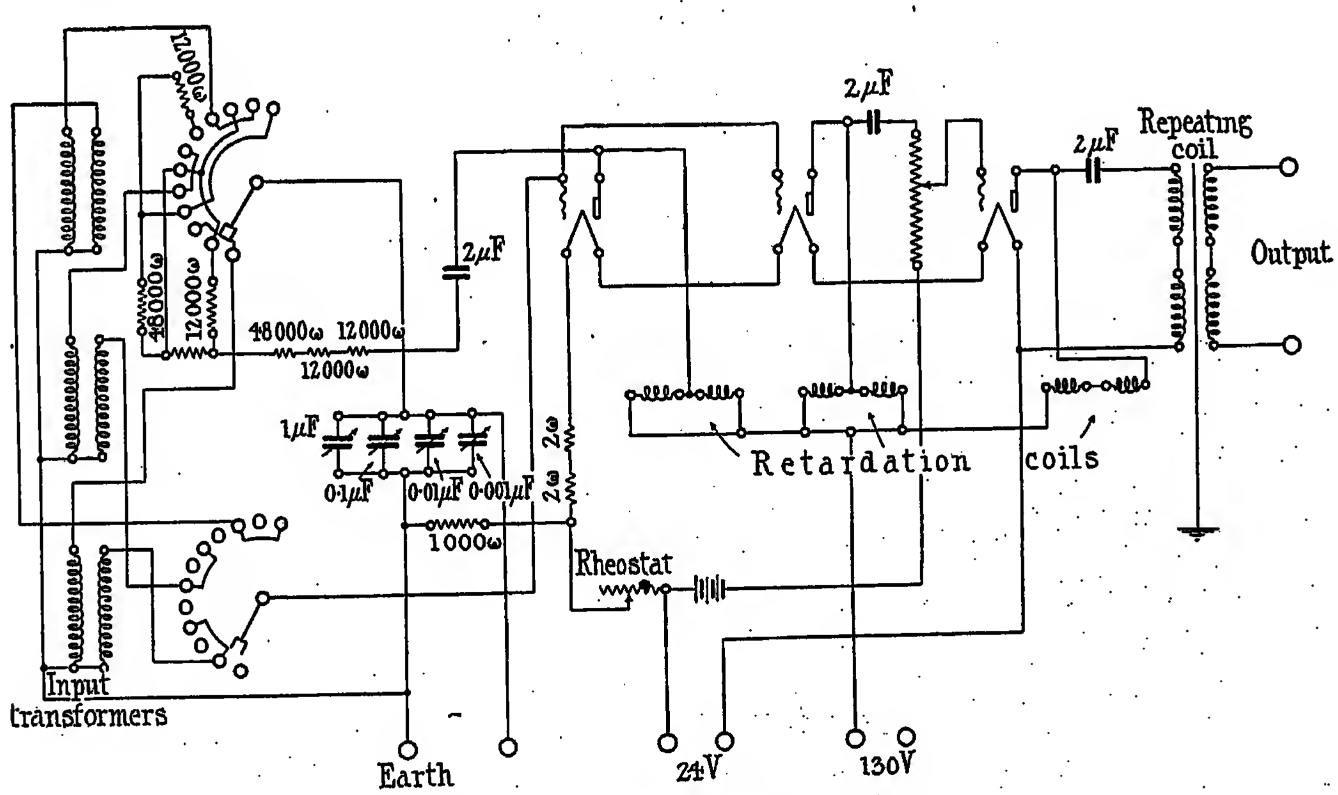

FIG. 18.—Circuit of "4-B" oscillator.

receiver. The set has a range of from 0 to 11 110 ohms and − 0·530 to + 0·530 henry, and an accuracy of about 1 per cent.

With both the 2-A impedance unbalancing measuring set and the 1-B impedance bridge, testing current is usually obtained from the 4-B oscillator.

The circuit of a 4-B oscillator is illustrated in Fig. 18. It is a typical vacuum-tube oscillator which is used in

paper to describe in great detail each testing instrument. The information which we have been able to include will, we hope, be of some assistance to telephone engineers who are not already familiar with the transmission maintenance practices herein advocated. We believe that the time is not far distant when these useful tools will be regarded by the maintenance forces of telephone administrations as being as indispensable as

the Wheatstone bridge is to-day and that they will form part of their regular equipment in the future.

Successful transmission maintenance depends more upon the dissemination of sufficient knowledge throughout the rank and file of the operating staff, than upon expert knowledge possessed by officials at headquarters.

In conclusion, the authors desire to acknowledge their indebtedness to the American Telephone and Telegraph Company and the Western Electric Company for much of the data contained in this paper.

APPENDIX 1.

Location of an Irregularity by Means of Impedance/Frequency Measurement.

Assume that in an otherwise uniform line (Fig. 19) an irregularity occurs at a distance D from a testing point. It is desired to locate the irregularity by means of an impedance test over a range of frequencies. The velocity of wave propagation is known from considerations of the constants of the line. Let the velocity of propagation be V.

The voltage impressed at the testing end causes a current to flow in the line. A portion of this current is reflected because of the irregularity. The distance

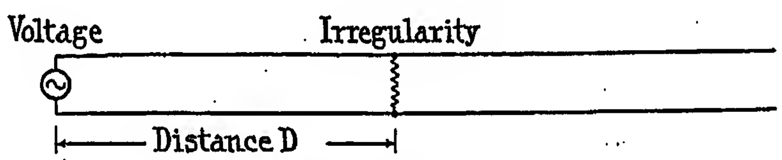

Fig. 19.

traversed by the direct and reflected current is $2D$, and the total time that elapses before the current returns is $2D/V$.

If the current which returns from the irregularity is in phase with the impressed voltage, when it returns to the sending end the apparent current-flow into the line will be greater than would be the case if the line did not contain the irregularity. This means that the ratio between the impressed voltage and the current, i.e. the impedance, is at a minimum value.

As the reflected wave has taken $2D/V$ seconds to make the return trip, if we assume that it has a frequency of f cycles per second, there will be $2Df/V$ complete waves between the sending end and the sending end on the return trip.

If we now vary the frequency of the impressed voltage either up or down, it will be seen that the reflected wave will no longer be in phase with the impressed voltage. This means that the impedance is no longer a minimum, but is increasing. As we vary the frequency the phase will change until a point is reached where the waves are again in phase. This means that there will be one more, or one less, complete wave than in the previous case of the frequency f. Expressed in equation form :—

$$2Df/V = 2Df'/V \pm 1$$

or

$$D = \pm V/2(f - f')$$

Assume an open-wire line in which the speed of propagation is 180 000 miles per second. Suppose the irregularity causes maxima values of the impedance at 300, 600, 900, 1 200 cycles. The interval here, that is $(f - f')$, is 300 cycles. The distance to the irregularity from the end is therefore $180\,000/(2 \times 300) = 300$ miles.

APPENDIX 2.

New Unit for Transmission Measurements.

Throughout this paper the standard-mile equivalent has been used to express transmission losses. This is the unit which has been in use for several years in Great Britain, the United States, and other English-speaking countries. On the continent of Europe it has, generally speaking, been the practice to express transmission losses and efficiencies in attenuation units (βl), that is, in natural logarithms at one or more chosen frequencies.

Recently the transmission engineers of the Bell System in the United States have introduced a new unit for transmission measurements and, since it presents certain distinct advantages, a brief reference may be of interest.

They define the unit in the following terms: The Transmission Unit is one such that two powers are said to differ by one transmission unit if they are in the ratio of $10^{0.1} : 1$.

The following are some of the principal factors that have led to its adoption :—

(1) The new unit does not vary with the frequency.

(2) The new unit is logarithmic in character and expressible in our common system of numbers. The logarithmic scale is used because the losses in the transmission line are a logarithmic function of the length. The logarithmic bases common in applied science are the Napierian base e and the common base 10. The latter is in more general use and tables of common logarithms are more readily available. Furthermore, the base 10 makes it possible to visualize the transmission unit more readily than the base e. Ten units correspond to a power ratio of 10, 20 units to a ratio of 100, 30 units to a ratio of 1 000, and so on. Ten to certain fractional powers very closely represents even ratios also. For example :—

	Approximately	Exactly
$10^{0\cdot 1} =$	1·25	1·259
$10^{0\cdot 2} =$	1·6	1·585
$10^{0\cdot 3} =$	2	1·9
$10^{0\cdot 4} =$	2·5	2·512
$10^{0\cdot 6} =$	4	3·981
$10^{0\cdot 7} =$	5	5·012
$10^{0\cdot 8} =$	6·3	6·31
$10^{0\cdot 9} =$	8	7·94
$10^{1} =$	10	10·0

(3) The new unit is based on a power ratio. The units which were in use are based on ratios of currents or voltages. In considering transmission problems we

are fundamentally concerned with the conversion and transmission of energy. We are usually interested in the ratio of the power delivered to the receiving set under one condition as compared with the power delivered under another or standard condition; or we are interested in the ratio of the power output to the power input of an apparatus or system. For many problems, especially since many long lines are characterized by uniform impedance, we may equally deal with current ratios or voltage ratios, but transmission engineers recognize that it is really the power ratio with which they are fundamentally concerned. The current or voltage attenuation unit corresponding to the one proposed is, of course, $10^{0 \cdot 05}$.

(4) The unit is of convenient size. For a good deal of practical work it is satisfactory to know the transmission equivalent of a long line to within one mile. Single-frequency measuring apparatus now in common use is calibrated to one-tenth of a mile, but seldom, if ever, in field work is there occasion for measurements to a greater degree of precision. It is desirable to have a unit in terms of which the losses and gains of interest can be expressed with the use of not more than one place of decimals.

Discussion before The Institution, 6 March, 1924.

Mr. S. A. Pollock: The paper primarily refers to the provision of apparatus for an organized system of control in maintaining the efficiency of a telephone system. Anyone with experience of telephones will know that it is a very difficult matter indeed to control and maintain a large and complex system in a high state of efficiency. The need has always been felt for convenient and simple apparatus to enable the maintenance staff to supervise and detect any decrease in efficiency. The maintenance of a very large telephone system may be studied from various points of view. The present paper would seem to indicate that the method advocated is to centralize the supervision of maintenance. This method would apparently facilitate a central control in so far as it could enforce a periodical test of the various elements of a telephone system and get the report sent to headquarters for examination. Where the maintenance is centralized in that way, probably no better arrangement of apparatus could be found except, perhaps, in line improvement. I do not think, however, that everyone would agree that the centralization of maintenance is an economic possibility. The apparatus described in the paper would undoubtedly serve the purpose of detecting losses of efficiency; but, as I understand it, when the loss of efficiency is discovered, with this apparatus there remains the location of the trouble and the remedy to be found for it. It is possible, of course, to deal with the question of maintenance in other ways, provided that the test was suitably devised for the critical examination of different parts of the circuit. In the case of a long telephone trunk line, if the organization admitted of each section of that trunk line being critically examined in such a way as to detect any fault, then the tests made would usually enable the fault to be immediately located. The same might be said for a critical examination of, say, a telephone repeater, and also for terminal apparatus such as the subscriber's. The subscriber's line, the connection to the exchange and the circuit might be examined piecemeal, and any fault discovered could generally be remedied by the person who is making the test. The overall test of a telephone line must necessarily be made from a terminal point, for instance from an exchange. The information obtained with this apparatus would, I understand, merely indicate that there is a loss of efficiency. My point is to emphasize the fact that the discovery of a loss of efficiency does not mean its location and solution. If tests are designed to locate a fault, then an efficiency test may be superfluous. On the other hand, sectional tests for the location of faults may not be possible in a great system, and I quite agree that such a method is hardly possible over every line in the country. But do the authors advocate that every line and every circuit should be routine-tested by apparatus of this description? If they do, can they give some idea of the cost of instituting a system or organization of that kind? It will generally be agreed that if it were economically possible every item in a telephone system should be periodically tested, but it may transpire that the cost of doing so would be altogether prohibitive. It is perhaps a question of policy as to whether the subscriber should assist in drawing attention to any fault that exists. He can give valuable information and assistance if anything goes wrong with his transmitter or with his local line, but a subscriber could hardly give much assistance in cases of faults in a long trunk line. The Post Office Department has considered this question of maintaining to the highest point the efficiency of very extensive plant. Probably the underground telephone trunk lines of this country represent the bulk of the extension, and the policy has been adopted of a periodical testing of these important trunk lines. But these periodical tests have been devised not to make the measurement of transmission efficiency, but to detect any defect whatever that arises after the line has been installed and tested for efficiency. The cost of the periodical testing of telephone trunk lines is probably insignificant compared with that of the routine test carried out in the manner suggested by the authors. Our experience shows that the routine tests which are adopted for telephone trunks do, in fact, draw attention to the slightest loss of efficiency, and they also enable the fault to be located at once. In fact, on the more important telephone trunk lines the method of routine testing adopted has had the effect of preventing any loss of efficiency due to faults. This is explained by the fact that the tests are devised to show the minutest defect before it can affect the efficiency of the line. Further, the tests would detect the defects which do not interfere with the use of the line. It would be of interest if the authors were to supplement the paper by information in regard to the localization of faults. The title of the paper is: "Transmission Maintenance of Telephone Systems." The subject might be regarded

as including the location of faults, and the problem of location has probably represented more ingenuity than has the devising of apparatus to discover the mere loss of efficiency. The authors raise very little controversial matter so far as the technical apparatus is concerned, but, having alluded to the economic side of maintenance testing, I think that the paper would be increased in value if the authors could supplement it by particulars of the personnel and cost, and the extent to which they would advocate the use of this apparatus on the system generally. There are, of course, the testing of telephone trunk lines, the testing of junction lines, the testing of subscribers' lines, and the testing of subscribers' apparatus. It is largely a question of cost. There is no difficulty in providing the apparatus for the purpose, as the paper clearly proves; but the question of how much money can be spent economically in routine testing is a very controversial point which I believe has been studied by many officials of the Post Office from time to time. In Appendix 2 the authors put forward a very interesting proposal to make a radical change in the practice of stating transmission losses of efficiencies. It is certainly attractive in its apparent simplicity. I understand that one of the arguments for adopting this new unit is the facility which it will afford for the construction and physical representation of the units. Some further information on this subject would certainly be welcome. In the last paragraph of the paper the authors state: "It is desirable to have a unit in terms of which the losses and gains of interest can be expressed with the use of not more than one place of decimals." In using the word "interest" do they refer to losses and gains of general interest to everyone, or of general interest to telephone engineers, or has the word some other meaning?

Mr. A. J. Stubbs: When, at one period, authority was given for the expenditure on maintenance for certain circuits serving Continental cables to be double the ordinary allowance the result was, not only that the circuits were available for a much greater proportion of time, but that the actual speed of the circuits rose, as far as I can recollect, by about 40 or 50 per cent. The value of this increased care in maintenance was further exhibited by the fact that when, through some change of staff, the arrangement ceased to function, the speed of the circuits altered sympathetically. Most telephone men would welcome the development of some other unit than miles of standard cable by which to express our transmission equivalents. The present unit involves that transmission equivalence is the inverse of transmission efficiency, which is not entirely satisfactory. The fact that to use an "ordinary" repeater coil instead of "the proper type" would lead to a loss of 1·8 instead of 0·7 brings into prominence the importance of ensuring that different items shall be readily recognizable both by design and by stock description. On page 660 we are told that lines loaded just before the war to improve transmission by the then latest known improvement have since been unloaded to secure the best results from the still later development of repeater working. This, as a sidelight, shows that the telephone engineer is quite prepared to make any changes that the rapid development of the art demands. I am not much in favour of the term "frequency spectrum" used on page 660. I would suggest that it be referred to the B.E.S.A. Nomenclature Committee before it becomes firmly established.

Mr. F. Gill: The economic importance of the paper lies in the fact that it gives a line of instruments which deal in the workshop fashion with transmission measurements, so that they can be used by the ordinary skilled man, who can thus grip the maintenance of the transmission part of the system. During the past few years a great amount of apparatus—condensers, repeating coils, shunts, loading coils, repeaters, etc.—has been introduced into the plant, all for the purpose of improving the transmission. But if these do not work, trouble may remain undetected for some time. In an ordinary exchange there are 34 non-inductive shunts and supervisory relays to every "A" operator's position. With 100 such positions in an exchange, there are 3 400 such relays and shunts in use in that exchange. If the exchange has been installed a few years, it is not beyond the bounds of possibility that some of those things may have gone wrong. The paper indicates a ready means of detection which can be used quickly and easily by the regular maintenance men. That is where the importance of this matter lies. The economic value of noise is given as the difference between a 30-mile and a 45-mile standard. If we can measure the noise, and if we can keep it down, we are doing something which is of great economic value. Mr. T. G. Miller, the General Superintendent of the Long Lines Department of the American Telephone and Telegraph Company in the United States, in connection with that plant containing 1 115 000 miles of wire, including overhead wires carried on 27 000 miles of pole line, says: "During the past few years the extensive use of repeaters, complicated cable circuits, carrier telephone and telegraphs, has made better transmission measurements necessary. Without these instruments it would be difficult, if not impossible, to maintain a satisfactory service over many of the circuits in use at present. . . . Eighty-five per cent of all the long lines, including all the more complicated circuits, are now being measured regularly at transmission measuring desks." I take it that one of the things he says is, in effect: "Use these things where it pays, and do not use them where it does not pay." Another use to which they are being put is to check up exchange equipments and toll cables at the time of construction. The authors point out that measurements can be made within something like $\frac{1}{2}$ mile to $\frac{1}{10}$ mile. In the older method, viz. by speech tests, it is quite difficult to make a measurement of that small amount, but it is quite simple, particularly with visual indication, for the maintenance man to measure down to $\frac{1}{10}$ mile, by using these instruments. Mr. Pollock mentioned the centralization of maintenance. From my knowledge of American telephone companies, I do not think that they are likely to centralize anything except major decisions. Their disposition is to push the work of maintenance down the line, and to make everybody do his share. But there is such a thing as centralization of control, such as one gets on board a steamship, where, while the different people do their work, the major decisions are taken at one central place. A means of obtaining

control is by the circuit lay-out; the ordinary telephone line is the resultant of many losses and gains; the circuit lay-out is practically the specification for the line, and determines exactly how the line should work. These circuit lay-outs are made by a committee which sits daily, on which the traffic, engineering and plant branches are represented. The new proposal in Europe is a system of organizations, each one carrying on its own work, with a consultative committee meeting at long intervals and having a permanent office for collecting information. I do not see how the work of making circuit lay-outs, the quick answering of questions as to facilities, and the direction of a long lines service can be done by that type of organization. In my opinion the European International telephone system will sooner or later have to accept some kind of unity of direction.

Mr. A. J. Aldridge: Routine testing is of the utmost importance, bearing in mind the tremendous amount of apparatus that is now in use in many telephone connections. Judging from the figure given on page 666, of the average loss of 15 miles due to noise on the lines, routine testing would appear to be rather more necessary in America than in this country. I should be glad to know what that noise really is. I cannot conceive any lines producing that noise being tolerated at all in this country. Transmission testing sets such as those described in the paper are not peculiar to America, and Mr. Pollock has referred to some that have been designed in England. One set of which I have knowledge is a portable set designed primarily for testing junction lines. A junction line very frequently consists of a large number of short lengths of cable. There may be one or two exchanges in circuit and generally, as the line has no definite line impedance, it cannot be closed through a fixed similar impedance; some test other than that suggested by the authors is therefore necessary. Also, that method of testing by closing the line through its own impedance is not altogether satisfactory, as the constants of the line have to be known. The set to which I refer is arranged in two parts, the first containing an oscillator giving a frequency range of 500, 800, 1 100 and 1 500 cycles, a screened transformer, an artificial trunk line and an ammeter. The other set, which is used at the receiving end of the line, contains an amplifier-rectifier arrangement similar to the one given by the authors, a subscriber's average line, and a subscriber's average instrument. The measurement consists in obtaining the ratio of current sent into the trunk line to that received on the average instrument. A direct test is thus obtained of the complete circuit used as it would be in practice, i.e. terminated at one end by a trunk line and at the other end by the instrument. If desired, the galvanometer can be calibrated to read direct in standard miles. I should be glad if the authors would give a little more information about the noise-measuring set referred to on page 666. The standard noise is apparently produced by a vibrating element, but that does not seem to be the most suitable method. Variations produced by changes in the contacts, and changes in the reed frequency from several causes, would appear to destroy any claim to constancy. We have been developing a set on similar lines, but I think it is an improvement. An alternator produces the standard noise, which is compared with the disturbance on an ordinary cross-talk meter arrangement in the usual way. To facilitate balancing, we have adopted an arrangement which, I think, other investigators have found to be very satisfactory, i.e. a kind of flicker meter. The currents producing the two sounds pass through a commutator on the alternator shaft and are rapidly interchanged in the receiver. By that means it is possible to compare two sounds of quite different character, and different observers are found to obtain results much more in agreement than they would by a simple comparison of the two differing sounds. I am not quite clear how the authors' test is carried out. On page 667 they say that the test is made by comparing the effect on conversation of the disturbance and of the standardized noise. Judging from Fig. 6, I should imagine that direct comparison is made between disturbance and the standard noise, without any speech test at all.

Captain B. S. Cohen: Although the methods of machine transmission testing, that is, methods other than the use of the voice and the ear, are of great value for trunk-line testing, in my opinion they are of even greater value for the transmission maintenance of the terminal lines, circuits and apparatus. A multiplicity of junctions and subscribers' lines, subscribers' apparatus, private branch exchanges, exchange circuits and wiring losses are all connected to the trunk line, and with recent improvements in the design of the trunk lines and in repeatering, the percentages of the overall transmission losses localized in this terminal apparatus are becoming more and more formidable. From the point of view of transmission maintenance the trunk lines which terminate in test-rooms are of course more easy to deal with than the terminal circuit, apparatus and lines. Like so many other advances, the introduction of machine transmission testing apparatus was delayed by the war, although standard cable-balancing sets operated by speech and ear have been in use in exchange testing rooms for some years. Three types of apparatus have been developed in this country, to two of which Mr. Aldridge has already referred. These are a set for general maintenance transmission testing, a disturbance measuring set and one for repeatering and trunk-line maintenance testing. Reference is made on page 657 to a simple and inexpensive means of checking the working and efficiency of subscribers' transmitters and receivers. Details of this, when available, will be of great interest, in view of the fact that by far the greatest variation in transmission efficiency can take place in this apparatus. A rhythmic oscillator has already received attention in this country for this purpose, the rhythm of which will govern the audio-frequency range. In Table 1 figures of abnormal losses and their causes are given. When the first machine transmission testing set was developed in this country two or three years ago, it was first used to straighten up some tangles left by the war at a provincial junction centre, and some faults discovered by its use may be of interest. For example, a cord circuit with a normal loss of 2·5 miles of standard cable (m.s.c.) had an excess loss of 4·3 m.s.c., which as a result of this test was immediately traced down to a faulty repeating coil. In

two other cord circuits, with a normal loss of much the same order, there was an excess loss of 3·4 m.s.c. due to faulty bridging coils. The point which must be emphasized is that no other test would have been capable of finding out these faults with the apparatus in situ. On page 665 the authors give a transmission efficiency chart commencing with intelligibility, for which we use the term " audibility." We consider that audibility is the resultant of three main factors—volume, articulation and interference. We group volume and articulation as being factors of the frequency/amplitude characteristic of the apparatus, which is the same as the authors' frequency response. As regards non-linear distortion, although in general this effect is only noticeable with repeaters and transmitters, it should be made clear that it is capable of occurring with other apparatus such as receivers, and even transformers under special conditions. In common with Mr. Aldridge I should be glad of some further information with regard to the noise-analysing set mentioned on page 666. The figure of 15 m.s.c. referred to as the loss due to maximum normal noise appears to me to be extraordinarily large, and is considerably in excess of the normal maximum loss due to interferences in this country. In general, we are in favour of the new unit mentioned in Appendix 2. There are, however, certain costs involved in its adoption in the way of altering standard cable sets and other apparatus and also in records, and before incurring these we should like to see other countries in agreement.

Mr. G. D. Edwards: I have just returned from a very active personal contact with the installation and placing in service of a long trunk cable system, in which I have seen many of the methods and even of the instruments described in this paper applied with distinctly satisfactory results. In fact, as I look back upon the course of the work, it is difficult to see how it could have been completed satisfactorily without many of them. The cable system which I have mentioned is that between Stockholm and Gothenburg in Sweden and is roughly 330 miles in length. It is loaded, of course, and repeaters and testing facilities are installed at its termini and at six intermediate stations. Its longer circuits, such as those connecting Stockholm and Gothenburg, contain as many as four repeaters operating in tandem. The system was taken into operation completely in September of last year. In the installation of the cable and loading for this system, a number of the instruments and methods described by the authors have been found of exceedingly great value. In this connection I have in mind more particularly the singing-point tests for the detection of irregularities, and the impedance/frequency measurements for their location. Some such instruments as the authors have described are a necessity in the installation of repeater equipment, where the gain/frequency and impedance/frequency characteristics of the amplifying and associated equipment must be thoroughly check-tested before any repeater station can be considered ready for service. A mere attempt to place in operation such a cable system as that between Stockholm and Gothenburg, stretching only over a distance of little more than 300 miles and never involving the operation of more than four repeaters in tandem, will provide anyone with convincing proof of all that the authors have said with regard to unity of control. I believe that the experience with this Swedish cable may be said to have proved the efficacy of unified engineering and operating in connection with long repeatered cable systems, and of the general direction of maintenance activities by a central authority. This does not mean that all maintenance activities must be carried on by that central authority, but it does mean that there should be a single source of general maintenance policies and plans. The Swedish telephone administration was very quick to realize the importance of these factors, and has made the small changes in its organization and operating methods necessary to bring about this essential unity of control. I believe that I can say unreservedly that the results have been most gratifying. Many of the methods and instruments described in the paper are now in regular use on the Stockholm–Gothenburg system in connection with its transmission maintenance. It may be said that their value for this purpose also has been proved, at least so far as this system is concerned. What I have said so far applies only to the application of these principles in a single instance, but the case in question involves what I believe to be the longest loaded repeatered cable system now in operation in Europe. I believe that further and longer experience with such systems will only serve to increase the conviction that these principles are most important and that the methods and instruments described are very valuable tools in connection with the installation and maintenance of the long-lines telephone plan. I have had occasion in America to come into contact with the application of these newer methods of transmission maintenance to exchange area systems, and I am sure that their application to this portion of the telephone plant will prove of correspondingly great value.

Mr. E. S. Ritter: One speaker has already mentioned 15 miles of standard cable lost due to noise. I should perhaps put it in another way. The effect of a certain noise on a very short line will not be the same as the effect of the same noise on a very much longer line. Perhaps the authors will say if this accounts for the very high value taken. They state that with the transmission measuring set an accuracy of 0·1 mile of standard cable is obtained. I do not doubt that this is so in the general case where one has a uniform line to deal with, but I should like to know whether this accuracy is obtainable under the following conditions. At one end of a line there is a loaded underground cable with a medium impedance continued by an open line, and at the distant end of the open line a short section of non-loaded underground cable. The impedance at the two ends of the line will be different. I am rather curious to know whether the results given by testing would be the same from A to B as from B to A. Fig. 17 shows what the authors call a " 1-B " line impedance bridge in which a resistance is used in conjunction with an inductometer. In this country we prefer to use a bridge in which the measuring arm consists of a variable resistance shunted by a condenser. This will measure the line where there is a capacity angle, and when there is an inductance angle the condenser is joined in parallel

with the line. The results are very conveniently obtained in terms of conductance instead of impedance. The noise-measuring set shown in Fig. 7, as I understand it, enables the amount of what may be called the "inducing effect" of the noise present in the line to be compared with the noise received across the line; that is to say, the induced noise effect on the two wires in parallel to earth is compared with the actual noise heard when the telephone is joined across the line. This is a measurement of the state of balance of the line. In connection with heat coils, the authors say that a poor contact may add 1 ohm, or more, to the resistance. I have known a case in which the resistance has amounted to nearly 200 ohms in a bad contact at the heat coils. In another case a dry joint, the resistance of which was 20 ohms measured with direct current on the Wheatstone bridge, gave a loss of the equivalent of about 7 m.s.c. when measured with speech. In connection with the maintenance of underground cables, whereas a comparatively short cable such as is used for direct service between two exchanges is relatively unimportant, and the loss in efficiency would not be of much importance, yet on all cables short or long, or apparatus forming the links in a long-distance circuit, any loss in efficiency is a very serious matter. This country has developed, to a very high degree of precision, methods of testing for insulation and for further localizing any small drop in insulation. For example, it is now possible in, say, a 100-mile underground cable to localize a fault of the order of 300 megohms to within ± 2 miles. This can only be done if the cable is in good condition. Main cables now have an insulation of the order of from 10 000 to 20 000 megohms per mile. Any drop in insulation below this figure is generally due to some defect in the sheath of the cable, which it is possible to localize. Another most common type of fault may be described as the dry or badly soldered joint. This is comparatively difficult to localize, although it causes loud overhearing between a loop and its phantom circuit, but this has now been very successfully done by some new methods. Not only is a dry joint difficult to localize, but it is liable to disappear and come on again at some inconvenient time.

Mr. C. Robinson: Under the heading of "Unity of Control," the authors describe a test which occupies, according to the time stated, at least 25 minutes. It might be possible to deal with two or three circuits at once, but even then it would not be possible to carry out these tests at large stations where there may be 200 lines concerned. I suggest that it would be more practicable to make an overall test first from the control station; after which, if the line is not up to standard form, a detailed test should be made by the different repeater stations in the circuit. The routine tests made at each repeater station should ensure that the repeaters and balances are being maintained in proper order. With reference to the impedance/frequency characteristic of lines, the Post Office are working on the development of an oscillator on the heterodyne principle, the frequency of which can be changed continuously over the audible range. The oscillator also gives constant voltage over the audible range. It is proposed to apply this method to the rapid determination of the impedance/frequency characteristics of lines. An oscillator of this type was demonstrated at the last meeting of this Institution. The repeater gain-measuring set and the transmission measuring set described are similar in principle, if not in detail, to those developed by the Post Office. The form of instrument at present being developed by the Post Office combines the transmission measurement set with the repeater gain-measurement set. On page 677 the bridge used for measuring line impedances is referred to. We have experienced considerable trouble in obtaining accurate results when employing bridges which are dependent upon the use of inductances. The trouble is usually ascribed to the capacity of the windings of the inductances. Mr. Ritter has referred to the form of the bridge used for this purpose in the Post Office. It has one or two other advantages besides those which he mentioned, the chief being that the line balances can be calculated direct from the readings, without any intermediate calculation of the impedances.

Mr. J. S. Elston (*communicated*): The methods adopted to maintain telephone transmission in the various countries no doubt appeal to each administration as best suited to its needs. Mr. Pollock has explained that, in this country, telephone engineers place much confidence in the systematic testing of covered work with a view to the discovery of potential trouble at a very early stage, and in periodical routine testing, combined with the patrol of routes, for open work. In view of the precautions taken to ensure the good maintenance condition of the long-distance loops, it is somewhat difficult to accept the suggestion of the authors that the London–Glasgow telephone trunk circuits—approximately 425 miles of 800-lb. loops—could be degraded to the transmission equivalent of 300-lb. loops without a previous indication of trouble. Nevertheless, no telephone engineer, particularly if immediately concerned with the transmission qualities of telephone plant, would deny the need of testing instruments which will enable a direct comparison to be made, easily and accurately, between theoretical transmission values and the transmission obtained in practice. It is a requirement which has occupied the attention of Post Office research engineers for some considerable time, and earlier contributors to this discussion have indicated the general lines of development. Mr. Gill mentioned circuit plans, and it is assumed that these are, in effect, transmission lay-outs. It is curious that the practical aspect of transmission theory is so seldom referred to and receives such scant attention in technical papers. Given a standard transmission, it is the method of circulating and controlling traffic which determines circuit or transmission lay-out; and transmission lay-out, in turn, determines the plant lay-out. In a going concern the plant will consist of all types of construction, some obsolescent and some up-to-date. The external plant may be open or covered, and, if covered, unloaded or loaded. Single circuits may consist of one or other of the types, or a combination of types of construction. In switching operations the combinations are many and varied, and the individual circuits are generally short lines electrically. The transmission calculations are very difficult, and figures, such as the authors quote as constituting good practice, can be criticized only when

the critic has a full knowledge of the traffic range and the combinations of line circuits and apparatus which will be linked together. Notwithstanding the fact that theory indicates the combinations which should be formed to obtain the best transmission, many problems in economic plant lay-out await solution. It is not always possible to match impedances so as to incur inappreciable losses, and transition losses may then become important in adjusting transmission to traffic circulation. This is particularly so in this country where direct-current signalling is largely used; terminal transformers, at present, cannot be inserted in the circuits to bring them to a common impedance. I think the authors could have made a claim that testing instruments of the character described have considerable possibilities in bridging the gap between transmission theory and the values obtained in practice. A testing instrument which would give reliable transmission tests under practical conditions between two subscribers linked together by various combinations of line circuits and apparatus would enable engineers responsible for external telephone plant lay-out to plan with greater certainty and more confidence.

Mr. A. B. Hart (*communicated*): The authors have stated the case for greater precision in transmission measurements in telephone systems very clearly and completely, but in regard to methods and means there are some points in which further elucidation is desirable. The determination of the transmission efficiency of any telephone apparatus or network involves the measurement of small alternating currents, and it is important in studying a paper of this kind to have a very clear idea of the magnitude of the currents to be dealt with. It may therefore be useful to state that, for example, in an average repeater section 50 miles long in a modern long-distance cable, the magnitude of the currents transmitted is of the order of 1 to 2 mA at the sending end of the section and $\frac{1}{5}$ to $\frac{2}{5}$ mA at the receiving end. The mean frequency of these currents is generally taken as 800 cycles per second. It will be obvious to all engineers acquainted with methods of measuring small alternating currents that the design of commercial instruments to deal with currents of the order of those just quoted with an accuracy anywhere approaching that mentioned by the authors in their description of a transmission measuring set, presents some difficulties. A calibration to 0·1 standard mile is mentioned; in other words the detection and measurement of differences of the order of 1 per cent in a current of 0·2 mA. There is no doubt that such accuracy and precision can be obtained, but it is very important to appreciate the possible sources of error that may arise in translating these readings into terms of transmission efficiency involving the expression of a ratio between sent and received currents. Mr. Ritter has indicated difficulties that may occur in dealing with composite lines. These probably present the most severe conditions, but even in a cable network of nominally uniform characteristic impedance it will be found in practice that circuits differ in capacity to an extent sufficient to cause impedance/frequency irregularities which make it difficult to predetermine the actual line impedance at a given frequency. Consequently, single-frequency measurements cannot be relied upon to represent, with sufficient accuracy, the actual commercial speech-transmission efficiency of any given circuit, and a method of measurement involving a range of frequencies is to be preferred in practice. In describing "Noise Conditions" the authors state that line noise is generally due to inductive interference from external power circuits. So far as the telephone line network of this country is concerned, this statement is not quite accurate. It is true that serious interference has been caused by power circuits, but the principal source of disturbance has been the high-speed telegraph system. Where high-speed telegraph circuits are carried upon the same pole lines as high-grade telephone lines it is necessary that the latter should be maintained at a high degree of balance, particularly when long-distance phantom circuits are operated. The disturbance created by a high-speed telegraph in an unbalanced telephone circuit is of such a nature that the question of measuring and analysing the noise never arises. The noise must be eliminated entirely and the problem resolves itself into locating the cause of unbalance in the telephone circuit. Long-distance aerial circuits with conductors weighing 1 200 and 1 600 lb. per loop-mile are, by the mere fact of their high efficiency, subject to disturbance by slight faults that would hardly affect a short-distance light-gauge circuit. Such faults as badly soldered joints, loose or corroded fuse fittings, cracked insulators, cobweb accumulations, intermittent tree contacts and last, but not least, imperfect regulation in the pole-to-pole spans will set up noise conditions that may prove very troublesome to diagnose and locate. Even the most thorough system of inspection must be supplemented by precision apparatus for fault localization. Most of this apparatus is of course of the direct-current type and is perhaps outside the scope of this paper, but in recent practice the use of alternating-current apparatus for fault localization has increased and it is to be regretted that the authors have not been able to include some description of such apparatus in their otherwise comprehensive paper.

Captain J. G. Hines (*communicated*): There is no doubt that steps should be taken to ensure that results which should follow the introduction of well-designed switching apparatus and scientifically planned lay-out of external plant are obtained. The work of the engineer is a combination of that of the scientist and the economist, as he desires not only to secure better results than have previously been obtained but also to do so in the most economical manner. Telephone apparatus is exceedingly complicated and much ingenuity is expended in devising appliances which will effect many combinations of connections without appreciably degrading the transmission efficiency at any stage. Exhaustive investigations are also made to determine the combinations of switching centres and cable systems which will ensure that each subscriber in a telephone administration shall be able to carry on a satisfactory conversation with any other subscriber with the least expenditure on plant. The calculations used in the determination of the lay-out of an area are based upon the normal transmission efficiencies of the cables and apparatus to be used. If those efficiencies are not obtained or are

not maintained, then much of the careful work that has been done is rendered abortive. It is essential, therefore, that checks shall be made to secure that the calculated efficiency has been achieved, or, if this is not the case, to ascertain the cause and location of the failure. The extent to which the checks should be applied to local lines is, however, a matter that requires very careful consideration, and the authors give no indication of their views upon the matter. There can be no doubt that in the case of long and very costly trunk cables the tests should be practically continuous and, as Mr. Pollock has indicated, this is the standard Post Office practice. Moreover, the tests instituted by the Post Office indicate not only the presence of an incipient fault before it has developed sufficiently to interfere with speech, but also the precise location of the trouble. In the case of local lines, however, there is not the same justification for the employment of staff and apparatus involving considerable expenditure. The lay-out of a telephone area provides for satisfactory speech when a subscriber is talking under the most severe conditions, that is, via the local and trunk exchanges to a subscriber in a remote part of the country. Although the local line and apparatus are designed to meet these conditions, it is only in a very small percentage of cases that the most severe conditions are experienced. Consequently there is nearly always a margin of loss that can be permitted without causing inconvenience to the subscriber. For example, the lay-out in London provides that speech between any two subscribers in the London telephone area shall not be worse than that over 18·3 miles of standard cable on a 300-ohm local line loop basis. Speech is commercially possible, however, over 35 miles of standard cable on the same conditions. A considerable loss may therefore take place without being noticed by a subscriber when speaking on local connections. Of course it is not contended that steps should not be taken to discover and remedy any loss, as the effect would be felt as soon as the subscriber makes a call on a long trunk line. The extent to which transmission testing should be carried out on local lines is, however, largely a question of economics. If the present methods of maintaining the high standard of trunk lines were applied to local lines the result would be reflected in the rates charged to subscribers for the use of the lines. It might be contended that a greater satisfaction with the service would result, but this would not necessarily follow, as subscribers do not require a volume or clearness of articulation beyond that which is necessary to enable them to hear distinctly. Complaints about poor transmission on local lines are comparatively rare. This is no doubt due to the great advances that have been made in recent years in the methods of planning telephone cable systems. It is possible, however, that there may be more complaints in the future, due to the rapid growth of wireless broadcasting. It is noticed that there is a tendency for subscribers to become more critical about the quality of the received speech. Only a few years ago it was a matter for wonder that speech should be possible over wires, and subscribers were satisfied if they could hear at all. Now they are not satisfied if the speech is less clear than that received on a wireless installation, with its remarkable freedom from distortion. This may render it necessary to obtain a higher standard than has been necessary in the past. Although systematic transmission maintenance testing has not hitherto been carried out on subscribers' lines, steps are taken to ensure that all installations are satisfactory before being put into use. The calculated value is supplied by the designing officer to the officer responsible for the final test, and his testing apparatus includes standard cable to enable a check to be made. This apparatus is also used to investigate complaints of poor transmission which may be made subsequently. If nothing can be found locally to account for the trouble, a chain of connections is set up to a central testing point and the loss is then measured. It is not infrequently found that the loss is in the exchange connections, due to one of the causes indicated by the authors in Table 1. Another cause is the use of a multiple jack, the interior surface of which has become dirty through infrequent use. A loss of 4 miles of standard cable has been traced to a fault of this character. It would be a serious item, however, to make regular and frequent transmission tests through all multiple jacks as well as through all cord circuits. I have no doubt that the paper will have the effect of directing attention to the importance of systematic testing, and the ingenious methods described will result in further measures being taken to secure the continuance of maximum efficiency at the least possible expense for testing.

Messrs. P. E. Erikson and **R. A. Mack** (*in reply*): If we understand Mr. Pollock correctly, he contrasts the relative advantages and disadvantages of two general principles of transmission maintenance, the first in which the overall efficiency of the circuit is checked by the periodical inspection and maintenance of each constituent part, and the second in which the overall transmission efficiency is measured directly and in a regular routine manner without separate tests upon the constituent parts. There can be no doubt that neither of these systems is sound in itself. The system with which we have dealt emphasizes the necessity of making direct measurements of transmission efficiency upon the circuits. Apart from whatever other tests may be considered necessary, it is only by the observation of overall transmission efficiency that the satisfactory condition of a circuit can be ensured. Any tests upon individual parts, while they may serve a useful purpose, can never properly establish the correctness of the connection between these various parts. In the event of overall transmission tests indicating a faulty connection it is, of course, frequently necessary to make individual tests upon the constituent parts, and it is definitely recommended in the paper that regular routine tests be made upon certain portions of the plant, e.g. tests upon the cable conductors for insulation and continuity.

Regarding the cost of carrying out regular transmission tests, it is regretted that no data are available which could be applied to the telephone system in this country. On the general question of economy, however, this, as indicated by other speakers, would be taken care of by arranging that the tests are carried out only when and where it is economical to do so. It has

been our endeavour to show that the advantages to be gained by the making of regular routine transmission measurements are much greater than have hitherto been realized by telephone engineers. The last sentence of Appendix 2 was intended to convey the argument that a transmission unit sufficiently small to enable the expression of transmission losses or gains occurring in practice with the use of but one place of decimals was preferable to a larger unit, in terms of which a loss or gain might have to be expressed in two or more places of decimals.

With reference to Mr. Stubbs's objection to the term "frequency spectrum," we would point out that this is a term which has come into prominent use in connection with telephony, telegraphy and radio-telephony. It is realized that it is not a term which, in its present application, has yet been officially recognized by any standardizing committee. However, bearing in mind that the frequencies involved in low-speed telegraphy, telephony, carrier systems and radio-telephony and telegraphy, each cover limited, though contiguous, portions of the whole frequency range, the application of this term seems particularly apt and we know of no other which conveys the general idea so well.

Mr. Aldridge, as well as other members, has questioned the example given on page 666, to illustrate the important part played by noise in determining the transmission efficiency of an average commercial connection. In spite of the opinions expressed by several speakers the facts as stated are correct, but to prevent misunderstanding it should perhaps be pointed out that the average noise assumed in this example includes all noise or disturbance upon the circuit due to causes other than room noise. There is no reason to believe, so far as our experience as telephone users is concerned, that the average line noise for an average connection on the system from which the example is taken is substantially different from that occurring in this country. This striking example was given to bring home to telephone engineers the very important part which noise undoubtedly plays in determining the intelligibility or transmission efficiency occurring in a large commercial system. The disadvantages of a vibrating type of noise standard, referred to by Mr. Aldridge, are quite real. These disadvantages have, up to the present, been met by arranging for a frequent checking of noise-generating elements against a standard element, and in care being taken in service to ensure that the noise element is carefully treated and not left running except when in actual use. A considerable amount of work has been carried out in connection with the development of a more suitable unit. At the moment this work is incomplete, but it is hoped that an improved unit will be available in the near future. For field use it is necessary that the noise-generating unit be small and portable, and this fact appreciably limits the freedom in design. We are not sure whether the noise generator referred to by Mr. Aldridge is of such dimensions as would enable its convenient use in field tests.

The use of the flicker effect for judging balances between sounds having widely different frequency ranges is not new; in fact it was used in investigations by Mr. D. MacKenzie, the results of which were published in the *Physical Review*, October 1922.* Since this time, however, further studies have convinced us that the flicker effect is not satisfactory, and the method has consequently been discarded. There can be no doubt that it greatly facilitates obtaining an apparent balance, but there is considerable doubt as to whether such a balance has much meaning on account of the introduction of overtones, which the interrupting of the sound would cause. It is necessary to use frequencies of at least 25 or 30 per second to increase the facility with which a balance should be made. These overtones may give a considerable change in apparent loudness and thus cause a false balance. In using this method for balancing two sounds, in which the frequency distribution is entirely at random, this effect would be a minimum, but in such cases there is little need for using the flicker method. In balancing out single frequencies, the addition of overtones would probably have the greatest effect and lead to the greatest errors in the results. It is in this condition that the method has its greatest apparent usefulness. We believe that for these reasons this method is not to be recommended. Mr. Aldridge is correct in assuming that in the method described in the paper a direct comparison is made between the disturbance and the standard noise without any speech test at all. The judgment of balance, however, is made upon the basis that the two sounds have equal interfering effect upon conversation.

Captain Cohen asked for further information on the noise-analysing set illustrated on page 666. This set consists essentially of a resonant circuit containing in series a receiver, a fixed inductance and a variable condenser. By suitably choosing the value of the condenser the circuit can be caused to resonate at any frequency between 150 and 2 500 periods per second. When in use the resonant circuit is connected to the circuit under test and the condenser is varied continuously from its maximum to its minimum value. When the condenser reaches such a value that the circuit resonates at the frequency of a harmonic present in the wave that is being analysed, a maximum tone is heard in the receiver; when this occurs, the setting of the condenser is noted and by reference to a calibration chart the corresponding frequency may be determined. In this way all the prominent harmonics present in a complex wave may be picked out and their frequency determined. The resonant circuit can be connected, by means of suitable keys, either between the two test terminals or between the two test terminals in parallel and earth. The first position allows the noise between the two wires of a circuit to be analysed, while the second allows the noise to earth to be analysed. Two terminals marked "110 volts" are connected to the two terminals marked "Test" through resistances of 1 500 ohms. These terminals are used when it is required to analyse a lighting circuit having a voltage not exceeding 110 volts, the resistances reducing the current in the receiver to a permissible value. A variable shunt is connected across the receiver to reduce the noise to a convenient amount. Captain Cohen's reference to the noise example has already been covered in the reply

* D. MacKenzie: "The Relative Sensitivity of the Ear at Different Levels of Loudness," *Physical Review*, 1922, vol. 20, p. 331.

to Mr. Aldridge. With regard to Mr. Ritter's question concerning the accuracy obtainable with the 3–A transmission measuring set, when a composite line is being measured, we think that there is some confusion. As we understand it the question has to do with the efficiency of the line composed of several sections of different construction. He asked whether the efficiency of such a line measured in one direction will be the same, within an accuracy of 0·1 mile, as that measured in the opposite direction. If such a line is measured between equal impedances, the result obtained in both directions will be the same within the precision of the measuring equipment. If, however, the value used for the sending impedance is different from that for the receiving impedance, the two results will differ because of the different transition losses occurring at the terminals in the two cases, since the impedances of the line are also different at the two ends. Either one of these two different results will, however, be obtained within an accuracy of 0·1 mile with this type of set, but these values do not necessarily give a correct idea of the efficiency of the line under normal use. It seems to us that Mr. Ritter has confused the question of the accuracy of the measurement *per se* with the question as to whether the result obtained is a true measure of the line efficiency under other conditions.

Mr. Robinson expressed a preference for an impedance bridge involving capacity elements rather than inductances. Our experience indicates that for the measurement of the small values of reactance which occur in line-impedance measurement it is more practicable to provide a simple bridge circuit involving inductance than a less simple bridge using capacity. As regards trouble due to the self-capacity of inductance coils, it is easily possible nowadays to design inductances in which these effects are sufficiently small to have a negligible effect upon the accuracy of line-impedance measurements.

Mr. Hines raises the question of applying checks to the transmission efficiency of local lines. The reason this question received small mention in the paper was that up to the present it has not been found possible to devise a testing system which meets the requirements for the measurement of local loop losses commercially and in a practical manner. It is perhaps worthy of mention that work upon this question has been proceeding for some time past and there are hopes that a means will be available in the future which will permit the easy observation of instrument and loop losses at a sufficiently low cost to warrant introduction for routine testing purposes.

PROCEEDINGS OF THE INSTITUTION.

716TH ORDINARY MEETING, 10 APRIL, 1924.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 27th March, 1924, were taken as read and were confirmed and signed.

The President announced that the Société Française des Electriciens had founded a Mascart Medal in memory of that eminent French scientist, the Medal to be awarded triennially to scientists or engineers of any nationality distinguished for their work in pure and applied electricity, and that the first (1924) award had been made to Monsieur A. Blondel, an Honorary Member of the Institution.

Messrs. H. Brazil and F. P. Sexton were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows :—

ELECTIONS.

Members.

Eckersley, Peter Pendleton.
Mulligan, Patrick.
Pedersen, Peder Oluf.

Associate Members.

Bean, Leslie Percival R.
Critchley, Vernon Fairbank.
Roberts, Albert Henry.
Simons, Donald MacLaren.
Velander, Sten.

Graduates.

Campbell, John James B., B.Sc.
Cantelo, Herbert Reginald, B.Sc.
Dickinson, James, M.A., B.Eng.
Fuge, William Valentine G., Capt., R.C.S.
Haldane, Thomas Graeme N., B.A.
Hothersall, William.
Needes, Edgar Charles.
Rawlings, William John.
Richard, Seward Thomas.
Samuel, Robert Philip.
Sheppard, George.
Whiteley, Arthur Wellesley.
Williams, Edgar John, B.Sc.

Students.

Aldridge, Thomas Jack.
Baker, Eric William.
Bennett, Arthur Edward C.
Bond, Richard, Jun.
Bottle, Edward Kelvin.
Brockbank, John Bowman.
Calam, Richard Hellyer.
Cartman, Clarence Noel J.
Comins, Richard Innes.
Cornwell, John Christopher.
Croft, Clifford Page.
Crowson, George Albert.
Dobelli, Alfred Clive.
Donald, Norman J., B.Sc.
Donnellan, Cuthbert.
Dunn, Arthur Charles L.
Fitzpayne, Eric Richard L.
Foale, Cecil William.
Foulkes, Heber Rees.
Gibb, Charles John.
Giddings, William Frank.
Gifkins, Reginald Tom.
Gilbert, Geoffrey Egerton.
Greasley, Ronald Andrews.
Grenfell, Alexis Rene.
Hollis, George Richard.
Holloway, Keith Henry.
Irvine, Harold Bartle.

Students—continued.

Kelly, Walter John.
Kingston, John Marshall.
Lindsay-White, Francis George M.
Lloyd, Reginald Albert.
MacGregor, Roderick Marcus.
Miles, Philip Pierpoint.
Miles, Thomas Snelgrove.
Miller, Thomas Taverner.
Moody, Denis.
Moss, Charles Geoffrey.
Myers, Frederick Horace E.
O'Meara, Alfred.
Parkins, James Walter.
Pearce, Cecil.
Pinkerton, George Stuart M.
Pollard, Zechariah.
Rogers, William Henry.
Seymour, Norman.
Shefford, James Herbert.
Steele, John.
Sumner, Herbert Laurence.
Turner, Arthur Stephen.
Turner, Ernest Alfred.
Tyson, William.
Urwin, Cecil Roland.
Ward, Frank Stanley.
Watt, David.
White, Henry Lachlan.
Whiteside, Harold, B.Sc. (Eng.).
Wilkinson, Thomas Edward.
Willis, Walter Stanley.

TRANSFERS.

Associate Member to Member.

Ballard, Leslie Walter.
Hamlin, Ernest John.
Hetherington, Edward Friend.
James, David.
Monkhouse, Allan.
Turner, Henry Cobden.

Graduate to Associate Member.

Herd, James Fleming.

Student to Associate Member.

Abernethy, John William A.
Hill, Norman Bartlett.
Hitch, Arthur Tyler, Lieut.-Col., D.S.O., B.Sc. (Eng.).
Johnson, James Ralph, M.(Eng.).

Student to Graduate.

Ashley, William Herbert.
Bartlett, Sydney John.
Bushell, John David.
Chawner, John Clement.
Jones, Harold Lancaster.
Padmanabhan, Catancolatur.
Price, Joseph Edelsten.
West, Frank Edward.

A paper by Mr. S. C. Bartholomew, Member, entitled "Power Circuit Interference with Telegraphs and Telephones," was read and discussed.

On the motion of the President a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7.50 p.m.

THERMIONIC VALVES WITH DULL-EMITTING FILAMENTS.

By the RESEARCH STAFF OF THE GENERAL ELECTRIC CO., LTD.

(Work conducted by M. THOMPSON and A. C. BARTLETT.)

(*Paper first received 30th November, 1923, and in final form 5th March, 1924; read before the* WIRELESS SECTION *2nd April,* 1924.)

SUMMARY.

An account is given of the history of the dull-emitting thoriated tungsten filament and of the development of thermionic valves containing these filaments. Intrinsic properties are described and discussed.

(1) INTRODUCTION.

Now that the thermionic valve has become a standardized engineering product it is of great importance in this progressive industry that the operating efficiency of the product should be increased to the greatest possible extent. Broadly speaking, there are two methods by which the efficiency of the valve can be, and is being, improved.

One method consists in so balancing the operating characteristics of the valve against the electrical constants of the circuit of which it forms part, that the maximum output is obtained from the valve with the minimum dissipation of power in the anode of the valve itself.

The second method, with one form of which it is proposed to deal briefly in this paper, consists in reducing the power consumed in heating the cathode to the temperature at which the necessary electrons are liberated from it. The discussion of this method is best introduced by a brief statement of the theory of thermionic emission.

(2) ELECTRON EMISSION (GENERAL).

The mathematical laws connecting the emission of electrons from substances with their temperature, were determined very completely by the pioneer work of Richardson,* who gave two general equations, both of which agreed with experiment equally well.

If i = saturated emission current in amperes per unit area of emitting surface, and
T = absolute temperature of surface,

then $$i = AT^{\frac{1}{2}}e^{-b/T} \quad . \quad . \quad . \quad . \quad (1)$$

or $$i = CT^{2}e^{-d/T} \quad . \quad . \quad . \quad . \quad (2)$$

where A, C, b, d, are constants characteristic of the emitting substance.

More recently, Dushman † has put forward on theoretical grounds an equation involving only one constant, characteristic of the emitting substance:—

$$i = 60 \cdot 2T^{2}e^{-b_0/T} \quad . \quad . \quad . \quad . \quad (3)$$

Whichever of these three equations is considered, it is obvious that at any constant temperature the magnitude of the saturated emission from any substance will almost entirely depend upon the value of the exponential factor b (or d). This constant, b, is related to the quantity ϕ, the work necessary for an electron to escape through the surface of the emitting substance, by the simple relation

$$b = \phi/k$$

where k = the gas constant for a single electron.

This relation between b and ϕ is confirmed by Richardson's proof that the contact difference of potential between two substances is equal to the difference in the values of ϕ for the substances.

Now directing our attention to the relation between i and ϕ, and neglecting the comparatively small effect of changes in the constant A (or C), we see that log $(1/i)$ is approximately proportional to ϕ/T.

In other words, at the same temperature substances having a low value of ϕ (i.e. electro-positive) will emit more electrons than will substances having a high value of ϕ; or, expressing the same statement in another way, the temperature at which we can get a definite amount of electron emission will be lower the smaller the value of ϕ or the more electro-positive the substance.

In order, therefore, to obtain most economically the necessary electrons for our valve, why should we not take the most electro-positive substance known and simply arrange to maintain it at the requisite temperature? The problem is not, however, quite as simple as that, on account of other factors, mainly those depending upon the physical and chemical properties of the substance.

Sodium, for example, will give 14 mA of electron current per cm^2 of surface at about 400° C., but it is easier in practice to heat a thin tungsten filament to 2 000° C. than it is to maintain a small amount of sodium at 400° C. Again, the vapour pressure of sodium at 400° C. is so considerable that we should no longer have a hard valve; and lastly, highly electro-positive substances are generally chemically reactive and cannot be maintained unchanged in the presence of any appreciable quantity of the residual gases, which are difficult to remove completely from an evacuated vessel.

Such considerations have so far prevented the use of any material but tungsten for the cathodes of large transmitting valves where mechanical strength is important and the removal of the last traces of residual gas almost impossible, owing to the high temperature attained by the anode. But in the smaller valves used for wireless reception and for the amplification

* O. W. RICHARDSON: "Emission of Electricity from Hot Bodies."
† *Physical Review*, 1922, vol. 20, p. 109.

of telephone currents, two forms of electro-positive cathode have been introduced. The first is the cathode covered with oxides of the alkaline earth metals. The great emission from these oxides at moderate temperatures was observed by Wehnelt * in the early days of thermionics. The Wehnelt or "oxide-coated" cathode has been developed very skilfully by the Western Electric Co. A very complete and authoritative account of their work is given by H. D. Arnold in the *Physical Review* (vol. 26, p. 76), and it is therefore unnecessary to offer any further account of it here.

The second form of electro-positive cathode is the thorium-coated tungsten cathode, with which alone this paper is concerned. It is usually known as the "dull-emitting" filament because it gives the requisite emission at a temperature much lower than that of the plain tungsten filament. This temperature is higher than that at which oxide-coated filaments are run, and consequently the term "dull emitter" might with even greater justice be applied to the latter. However, it is not generally so applied. It is unnecessary to discuss here the appropriateness of the nomenclature, so long as it is realized that by a "dull emitter" is here meant, not any valve with a cathode at a relatively low temperature, but only that form which employs the thorium-coated tungsten filament.

(3) History of the Thorium-coated Tungsten Filament.

The admixture of a small proportion of thorium oxide with tungsten has for very many years been common practice amongst electric lamp manufacturers when preparing their tungsten filaments, which as a result of this admixture are then less brittle than similar filaments not containing this or some other "impurity." For example, British Patent 18 467 of 1911 (W. D. Coolidge) claims the use of thoria and other refractory oxides mixed with tungsten powder before sintering, etc.

The first reference to any electrical peculiarity being shown by these thoriated tungsten filaments is contained in, and forms the subject matter of, two patents taken out in 1914 by Langmuir in America.† The first of these patents describes a method of heat treatment for such filaments, resulting in an extraordinary increase in the electron emission from the filament, the treatment consisting in heating the filament to a temperature of about 2 900° K. for a period of 1 or 2 minutes, followed by a few minutes at about 2 250° K. The electron emission from the filament was then measured at 1 380° K. and found to be equal to that obtained from a similar pure tungsten filament at about 2 000° K.

The changes brought about by this heat treatment were considered by Langmuir to be: (*a*) the evaporation of all gaseous and solid impurities from the filament surface at 2 900° K., followed by (*b*) the diffusion from the interior of the filament of thorium material which gradually formed a film covering the surface of the filament. The enhanced electron emission was then characteristic of this surface film of thorium material.

The emission from this activated or dull-emitting filament was, however, found to be quickly destroyed in the presence of traces of residual gas, and Langmuir's second patent describes a valve containing the dull-emitting filament and also a small amount of hydrocarbon or alkali-metal vapour, introduced in order to fix all those residual electro-negative gases which were likely to combine with the thorium on the surface of the filament.

Although no valves utilizing these dull-emitting filaments were being commercially manufactured at the end of 1919, the phenomenon could not escape the attention either of valve users or of valve manufacturers. It was a frequent occurrence during the war for thoriated filaments, especially in the hardest valves, to show unusually high electron emission, which sometimes survived several hundred hours of operation.* Also, in the actual manufacture of valves, during the electronic bombardment of the anode while the valve was connected to the pumping system, occasionally the electron emission from the filament would suddenly increase, as shown by the overheating, and even melting, of the anode. This phenomenon was generally associated with the presence of a more volatile metal such as copper, contained as an impurity in the nickel electrodes, and it was doubtless really due to a temporary development of the greatly enhanced thorium emission as a result of the action of copper vapour upon the thorium oxide in the filament.

One of the first problems undertaken by the Research Laboratories of the General Electric Co. was that of investigating the electrical behaviour of thoriated tungsten filaments, with the object of stabilizing their enhanced electron emission so that use could be made of them in valves.

Work was begun on the problem at the end of 1919 and a promising degree of success with receiving valves was fairly quickly achieved. Langmuir's results in regard to the effect of residual gases on the enhanced emissions were completely confirmed, and a method was evolved for producing regularly and with certainty a degree of vacuum considerably higher than that obtained in the average hard valve of that time. Further, it was found that, in addition to an extremely high degree of vacuum, it was also essential that all surfaces which collect electrons during operation of the valve should be free from adsorbed layers of gas. It was a comparatively easy matter by the classic method of electron bombardment to free the anode of the valve from all traces of gas, but much more difficult to do so with the grid.

The obvious method of heating the grid by passage of sufficient current through it was ruled out because experience had shown that a spiral grid with no damping wire was a cause of microphonic noises in the receiving set.

It proved possible, however, to cover the surface of the grid with a gas-free deposit or varnish,† after which deposition electron current could be passed from filament to grid for long periods (the grid potential being 50 volts or more) without liberating harmful gas from the surface of the grid, despite the fact that the grid metal certainly contained occluded gases.

* *Philosophical Magazine*, 1905, vol. 10, p. 88.
† U.S. Patents 1 244 216 and 1 244 217.

* B. S. Gossling: *Journal I.E.E.*, 1920, vol. 58, p. 682.
† British Patent No. 169 546 (Thompson and General Electric Co., Ltd.).

By June 1920 it was possible to draw up a schedule for the production of dull-emitter valves, and about this time, in order to test the process, the first fair-sized batch (about 50) was made at the works of the Marconi-Osram Companies by partially-skilled girl labour working in accordance with this schedule. Uniformly good valves were the result, and as a matter of interest the target diagram is reproduced in Fig. 1, which depicts the filament voltage and current required by these first 50 valves for the emission of 5 mA of electron current. Meanwhile, life tests under operating conditions of earlier valves showed steady electron emission for a period of 800–1 000 hours, so that by September it was possible to market the valve. Actually, the first large order was placed in March 1921 after considerable trial of sample valves.

The first type of dull emitter manufactured was then known as the "L.T.1" and, except for small modifica-

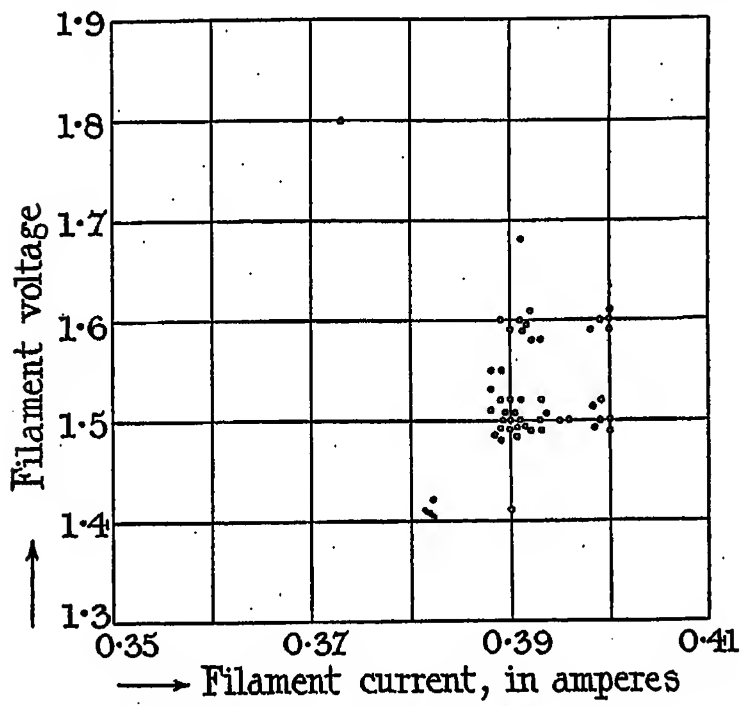

FIG. 1.—Target diagram for first 50 dull emitters produced in 1920: filament voltage and current required to give 5 mA of electron emission.

tions, has been in continuous production ever since, although it is now usually known as the "D.E.R." valve. The filament of this valve required 0·38 to 0·40 ampere of heating current at 1·5 to 1·8 volts, the total emission under these conditions being 5 mA. Compared with an ordinary tungsten filament of the same dimensions this showed a saving of about 75 per cent in the power consumed in filament-heating.

If the anodes of these L.T.1 valves were freed from gas by the usual method of electron-bombardment, a lower limit would be set to the filament diameter and, consequently, to the filament current, since filament wastage sufficient to cause the failure of the finest filaments always occurs during the process. If some other method of anode-heating could be adopted which would avoid this difficulty, there would be no lower limit other than that set by the mechanical strength necessary for the drawing down of the wire, for handling during the assembly of the valve parts, and also for the small amount of tension necessary to keep the filament straight inside the grid of the finished valve. It was known that induction heating by radio-frequency currents could be used for this purpose, and this was tried with success for the Royal Air Force, in collaboration with whose experimental department the trial was made. A valve oscillator was used for the generation of the high-frequency current. By this method, receiving valves were produced in 1920 in which the filaments required only 0·07 ampere of heating current at 1·8 volts, and also other valves having a lower anode impedance, in which the filaments consumed 0·1 ampere at 3 volts. Both these types (known as the "L.T.2" and "L.T.3") were made in small numbers in the Marconi-Osram works, but were not thoroughly satisfactory, chiefly on account of the great difficulty in applying the correct amount of tension to the filament. The margin of tension between that which would break the filament and that necessary to keep the filament off the grid was exceedingly small.

For valves in which filament tension is essential, about the right diameter of filament was found in the dull-emitter V.24 valve (D.E.V.), in which the diameter was gradually increased in successive trials until entirely satisfactory results both in the factory and in subsequent operation were obtained with a filament consuming 0·2 ampere at 2·7 to 3 volts.

The possibility of using as a dull emitter the thinnest filament of lamp manufacture has recently been demonstrated by the General Electric Co. of America, who have returned to the subject of the thoriated filament. They have met the difficulty of filament tension by using no tension at all, and arrange the dimension of filament length and grid diameter so that the filament on being heated does not expand sufficiently to cause it to sag on to the grid. This American valve takes 0·06 ampere at 3 volts and is truly within the capacity of dry cells. A similar type of valve is also made by several manufacturers in this country.

(4) PROPERTIES OF THE DULL-EMITTING THORIATED FILAMENT.

(*a*) *Contact-potential effects.*—When carrying out the first experiments on thorium emission in a complete triode, a valve of a standard type was used. Thorium emission having been stabilized, there appeared to be a considerable reduction in the grid current at zero grid voltage, and on plotting the usual anode and grid current characteristic curves it was clear that both curves were shifted bodily to the right, when compared with a similar valve containing an ordinary tungsten filament. The amount of shift was equivalent to about 1·5 volts on the grid. By plotting the characteristic curves before and after the formation of the thorium surface layer it was possible to demonstrate this particular effect with the same filament in the same valve (Fig. 2).

In addition to the bodily shift of the curves, the anode-current/anode-voltage characteristic was also less steep with the dull-emitting filament, while in diodes the saturation part of the curve was less flat than it is for tungsten emission. Both these effects are illustrated in Fig. 3. This lack of sharp saturation was ascribed by Langmuir to a kind of grid effect at

the heterogeneous filament surface which is not completely covered with thorium, the tungsten part of the surface acting in the same way as a negatively charged grid.

The effects described in the preceding paragraph necessitated the re-design of the electrodes, inasmuch as a slightly narrower grid of rather closer pitch was required to obtain approximately the same characteristic at the same operating voltages on grid and anode.

(b) *Stability of thorium emission.*—This question is of course of fundamental importance and, needless to say, always receives first consideration when new types of dull-emitter valves are being designed.

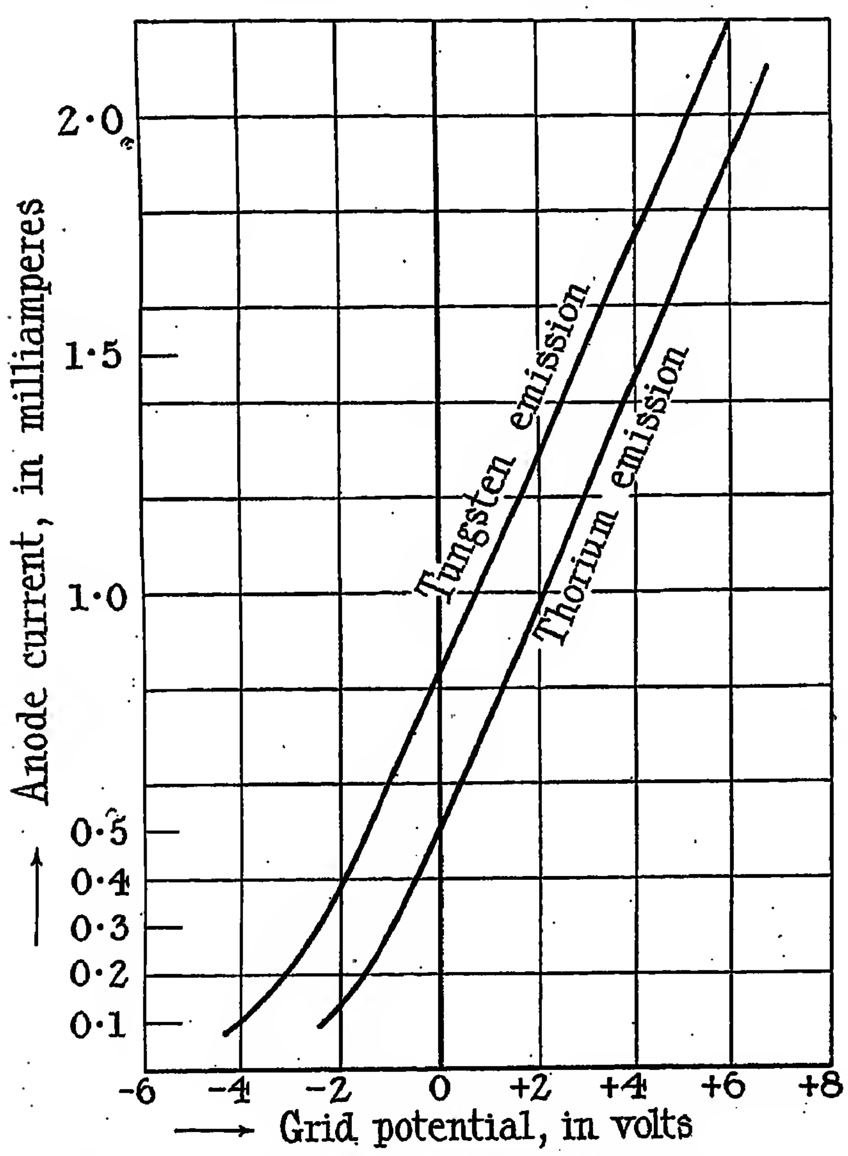

FIG. 2.—Anode-current/grid-voltage characteristics for one valve, with the same total emission (9·6 mA) from the same filament with (1) tungsten emission, and (2) thorium emission.

The three chief factors upon which depends the constancy of the electron emission from a dull-emitting filament were found to be: (i) Filament temperature, (ii) anode voltage, and (iii) the degree of vacuum. It is proposed to discuss these three factors in this order.

(i) Langmuir's early patents accurately described the effect of changes in filament temperature upon the electron emission from the filament. After the production of enhanced electron emission by heat treatment at 2 900° K. for about a minute, followed by 2 250° K. for several minutes, the emission was found to be steady over very long periods, during which the filament remained at a temperature of 1 700° to 1 800° K. If, however, the filament temperature were raised above 2 250° K., say to 2 500° K., the emission rapidly decreased until only the characteristic emission of pure tungsten remained.

By bringing the filament back to 2 250° K., however, the enhanced emission was again restored. The explanation of these changes, as being due to evaporation of thorium from the filament surface at the higher temperatures and diffusion from the interior of more thorium at the lower temperature, was easy to understand. It is not so easy, however, to visualize what happens during the original treatment at 2 900° K. which was found necessary in order to produce the emission, unless the actual formation of elementary thorium from its oxide occurs at this temperature.

Several thoriated filaments were therefore incandesced at 2 900°–3 000° K. for various lengths of time, after

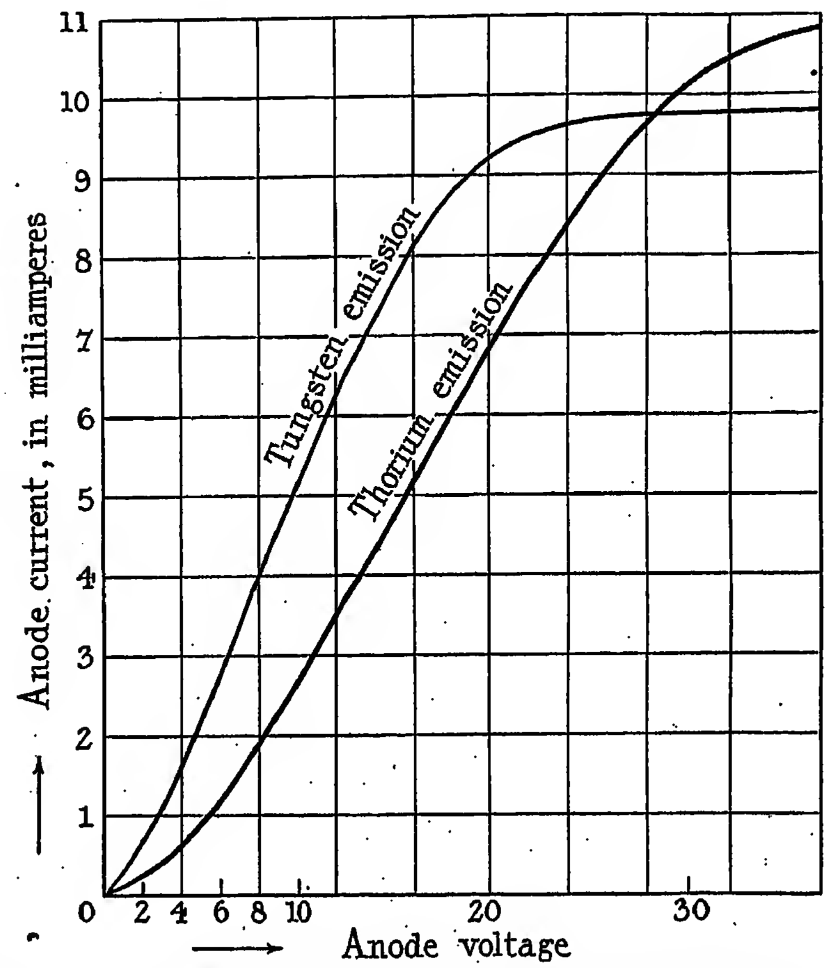

FIG. 3.—Anode-current/anode-voltage characteristics for two similar diodes: (1) tungsten filament and (2) dull-emitting filament.

which chemical tests were applied which could distinguish between thorium and its oxide. As a result it was found that after an hour's treatment at this temperature no oxide remained in a filament 0·06 mm in diameter, but that there was still present an amount of thorium of the same order of magnitude as that which would be equivalent to the original oxide.

Very numerous life tests carried out on valves have shown that, with filament temperatures not exceeding about 1 900° K., practically constant electron emission is obtained during periods which are very seldom less than 1 000 hours and are generally in excess of that

figure. In general, the life of the emission is longer the lower the temperature of the filament.

At the operating temperatures of 1 700°–1 900° K. our early results showed that some diffusion of thorium to the surface must be occurring, although much more slowly than at 2 250° K., for if for any reason, such as the presence of excessive residual gas, the electron emission decreased during the life test, it would increase almost to its former value if the filament was kept at the same temperature but with zero anode potential, so that no space current was flowing.

Langmuir * has recently attempted to separate the two factors (diffusion to the surface and evaporation from the surface) which govern the amount of thorium in equilibrium at the surface at any particular temperature. Amongst other results, he finds that thorium gas molecules which are always adsorbed on the surface of the bulb, the resulting positive ions then travelling to the filament, where they slowly but surely contaminated the thorium surface.

It was considered that in a larger bulb fewer electrons would actually hit the glass, and that those which did hit would do so with less kinetic energy, since they would be, figuratively speaking, travelling uphill. The energy of impact would consequently be less likely to be sufficient to cause ionization of adsorbed gas molecules.

In the light of these results a safe anode voltage was always stipulated for the various types of valves manufactured; for example, 30 volts in the V.24 bulb and 50 volts in the L.T.1 bulb of 25 mm diameter.

(iii) From the point of view of manufacture the deter-

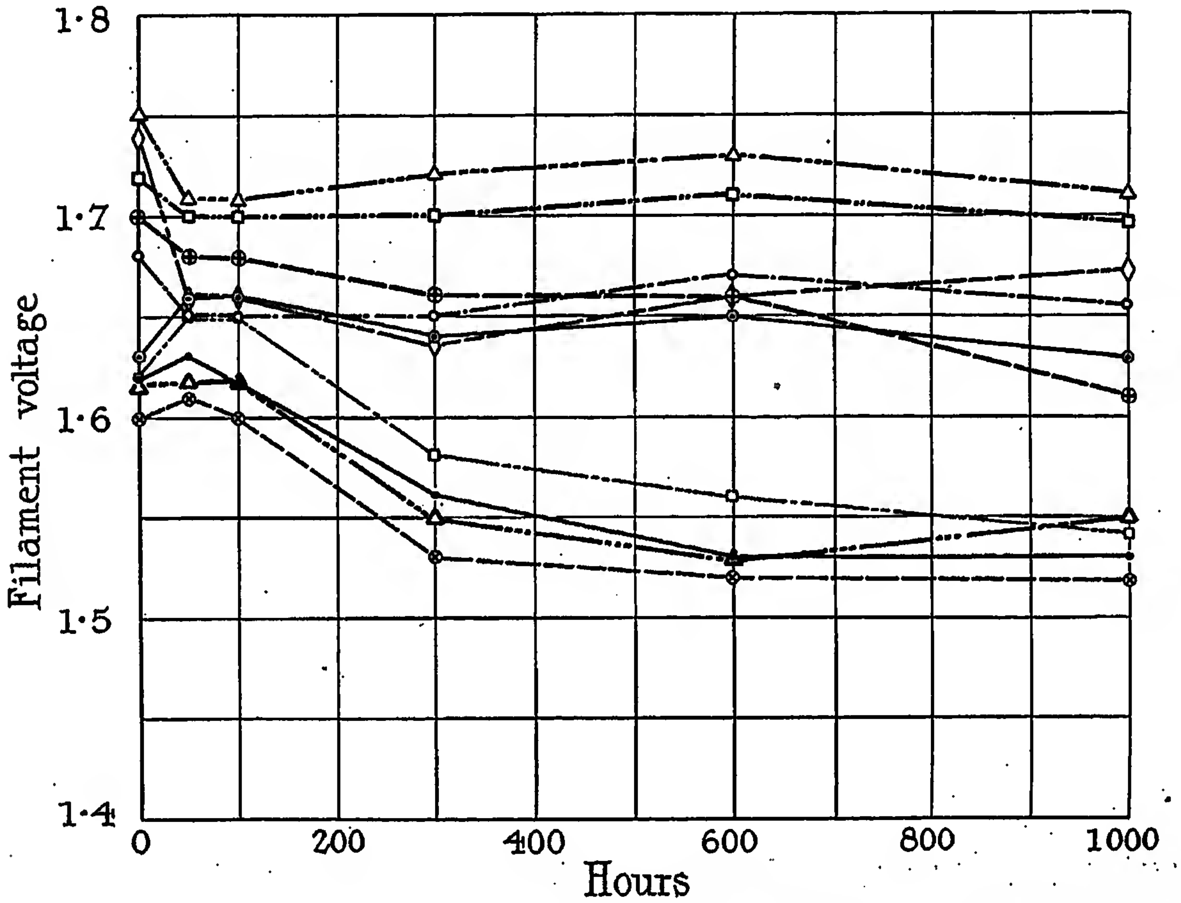

FIG. 4.—Life test of D.E.R. valves: filament voltage required to give a constant emission of 5 mA.

atoms evaporate from underlying thorium atoms at a rate very high compared with that of thorium from underlying tungsten atoms.

(ii) In general, and with other factors constant, the life of thorium emission in a valve was found to decrease with increasing anode voltage. Also the maximum anode voltage which would allow of a satisfactory life was a function of the size and shape of the enclosing bulb, the permissible voltage increasing with increasing bulb diameter. For a life of 1 000 hours, or more, the V.24 tubular bulb (of 15 mm diameter) was found to give this maximum at about 40 volts, while a tubular bulb of 25 mm diameter allowed about 80 volts, and so on.

This dependence upon bulb diameter seemed to indicate that stray electrons which followed circuitous paths to the anode were causing ionization of some of the

* *Physical Review*, 1923, vol. 22, p. 357.

mination of the degree of vacuum necessary for a satisfactory life of thorium emission is probably of more importance than any other consideration, for, in addition to the cost of an elaborate evacuation process, there is also the increased cost due to the proportion of valves which may be rejected on account of a degree of vacuum lying outside the specified limit.

In the early days of the development of dull emitters it was apparent from the results of life tests that, although thorium emission might be shown by the filament, in any particular valve this emission was not stable under operating conditions for more than 100 or 200 hours unless the degree of vacuum were very high, and, generally speaking, the higher the pressure of residual gases the shorter was the satisfactory life.

In order to obtain stable emission during a life approximating to 1 000 hours, the pressure of residual

gas had to be not more than about 0·00001 mm (of mercury).

This pressure was therefore aimed at as the maximum permissible, for it was of course realized that the future of the dull emitter would depend not only upon the great economy in filament-heating but also upon the satisfactory life which the valve gave under operating conditions.

However, except for occasional epidemics of "low vacuum," which were generally traced to their source, the proportion of valves rejected on this score was at first encouragingly small, and became progressively smaller as workers became accustomed to the manufacturing schedule.

It was realized that this upper limit of 0·00001 mm pressure of residual gases was somewhat arbitrary, inasmuch as account was taken only of quantity and not of quality of the gases. Experiments were therefore contrived with the object of finding out what was the effect of various pure gases upon thorium emission, the results of which experiments were to show that water vapour, carbon monoxide, and nitrogen all depressed the electron emission from a thoriated filament, even below that which is characteristic of tungsten itself, but that in the presence of hydrogen, even at a pressure as high as 0·01 mm, thorium emission was perfectly stable throughout a normal life.

If anything, therefore, we were erring on the safe side in setting a maximum limit of 0·00001 mm pressure; but as it was not possible to ensure that only hydrogen —and no other gas (particularly water vapour)—was present in the valve, this maximum limit was not altered.

(iv) *Life test.**—A small percentage of the Marconi-Osram works production is collected periodically (actually two or three times a week), and this small percentage is subjected to various tests by the laboratories, including life test.

With regard to the life tests on dull emitters, we may take the D.E.R. valve as an example. In our routine tests the valves are run with a steady a.c. filament voltage of 1·8 and anode voltage of 50, the grid being connected to one filament lead so that the grid potential virtually oscillates between zero and 1·8 volts positive. Except for the alternating voltage on the filament, these conditions are then very similar to actual operating conditions. The test is run on each particular collection of valves for 1 000 hours, measurements of emission, etc., being made at the end of 50, 100, 300, 600, and 1 000 hours. The emission measurement consists in reading the filament voltage necessary for obtaining a flow of 5 mA of electron current to the grid and anode, which are connected in parallel while the potential of 50 volts is applied to them. The filament voltage required is then plotted against the time during which the life test has run.

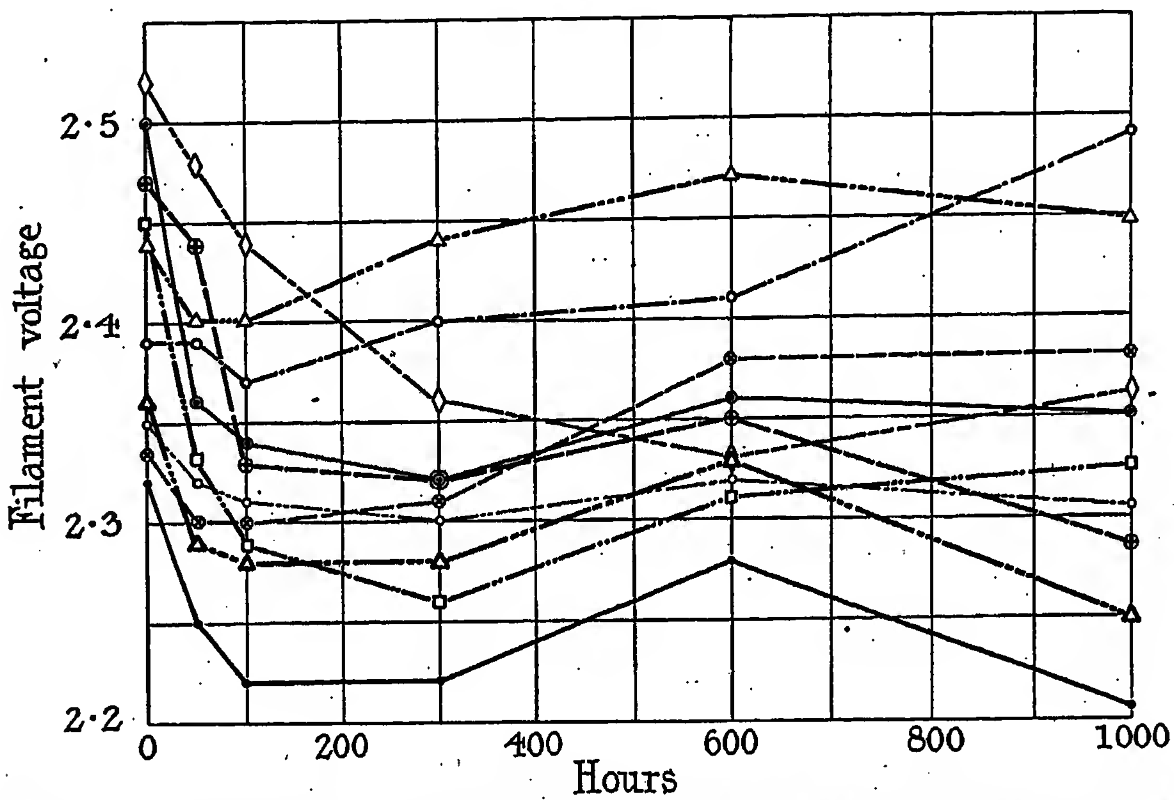

FIG. 5.—Life test of D.E.V. valves: filament voltage required to give a constant emission of 5 mA.

Typical curves obtained in this way for the D.E.R. valve are shown in Fig. 4, where the voltage scale is purposely made very open.

Similar curves for the D.E.V. valve, of which the filament takes 0·2 ampere at 3 volts, are shown in Fig. 5, and other curves for the power-amplifier valve (L.S.5) in Fig. 6.

(v) *Valve noises.*—Under this heading are included the two effects generally known as (*a*) crackling, and (*b*) microphonic noise. Both phenomena only become important in receiving circuits in which more than two stages of audio-frequency amplification are employed.

By the first term is meant the continuous series of sharp reports frequently heard in the telephones when valves with hot tungsten filaments are employed, and by the second term the more or less musical note

* The methods adopted in the life-testing of valves will be described in a later paper.

similarly heard when a blow or tap is delivered to a valve occupying a position before the last two.

The cause or cure of crackling has not proved easy to discover, although the phenomenon is generally looked upon as being due to impurities in the filament and although, also, the magnitude of the effect can be reduced to some extent by heat treatment of the filament.

Dull-emitting filaments are, however, almost entirely free from this first defect, but are offenders in respect of the second.

Very numerous experiments in connection with the microphonic noise characteristic of dull-emitter valves have driven us to the conclusion that the effect is entirely due to the filament retaining a high degree of in the offending valve by means of a low-power microscope, so that the effect of various types of electrode construction could be easily studied.

The first valve studied in this way was a 3-year-old one of the original L.T.3 type having a 70 mA filament current, and with this as the first valve the set was easily arranged to howl. When this occurred, no vibration of the grid, anode, or filament support could be observed with the microscope, but the filament bowed out to four or five times its original diameter. The same bowing out of the filament was also observed, but to a much smaller extent, in a D.E.R. valve.

A valve was next constructed having a small iron weight hanging from the filament spring so that by means of a solenoid the amount of tension on the

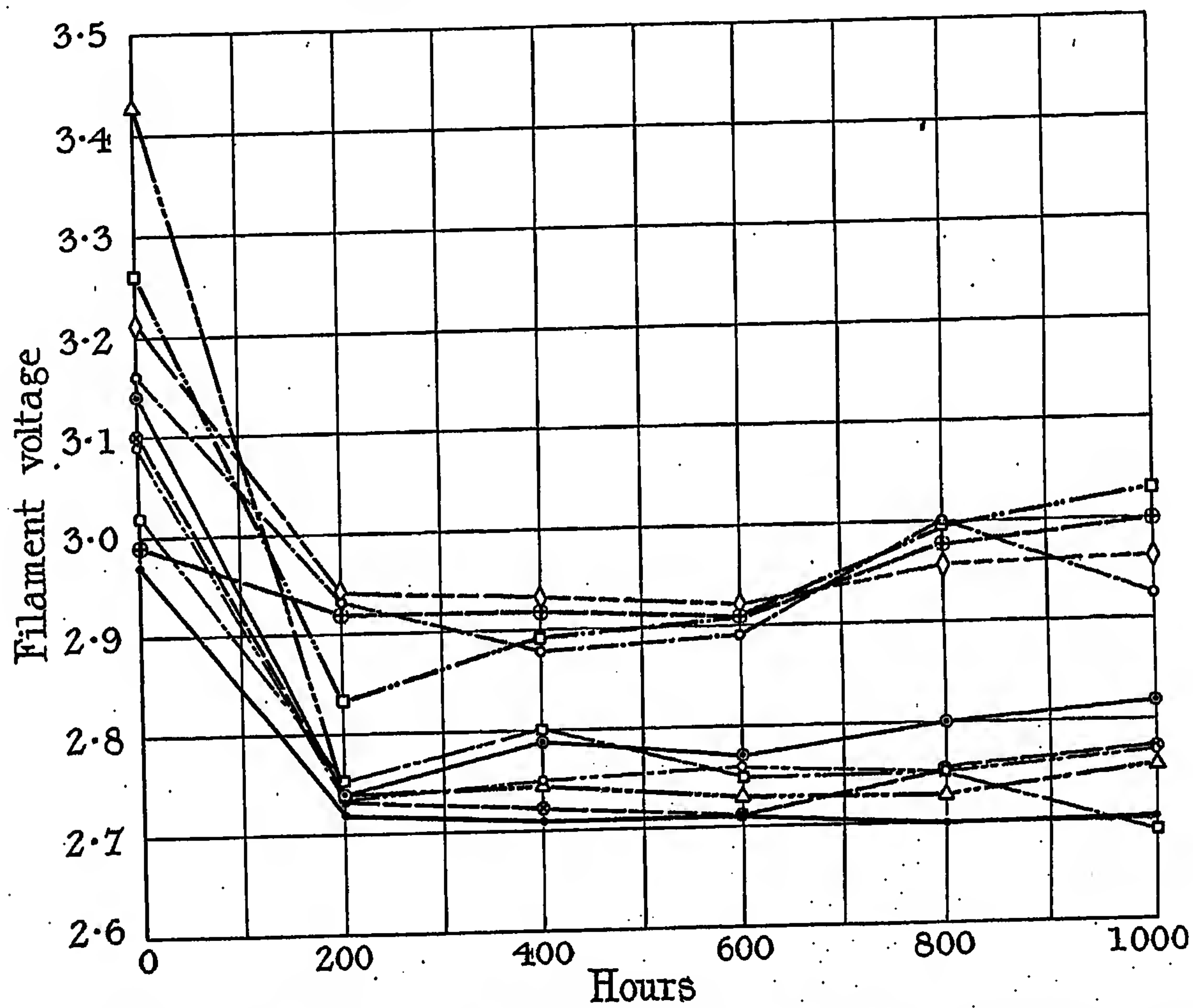

FIG. 6.—Life test of L.S.5 valves: filament voltage required to give a constant emission of 5 mA.

elasticity at its normal operating temperature. At present the only practicable method of eliminating these noises seems to be to mount the valve on a special type of holder designed to prevent any except very low-frequency vibrations from reaching the valve.

In carrying out the above-mentioned experiments use was made of the well-known howling effect which is obtained when a loud-speaker is used in conjunction with many stages (four or five) of audio-frequency amplification. Under these conditions, particularly when using dull-emitter valves, any signal or extraneous noise will start a persistent howl at a frequency near to the natural frequency of the diaphragm of the loud-speaker.

The persistence of the effect offered the readiest means for actually observing the electrode movement filament could be varied. It was found that by increasing the tension the pitch of the howl was raised slightly and the quality of the note was altered, but the general volume of noise was unchanged.

Various other valves were tried in this way with one or other, or all, of the three electrodes mounted on springs of very low natural frequency, and also with various bulb sizes, but no reduction of microphonic noise could be obtained.

There is no doubt, therefore, that these noises are due simply to the transverse vibrations of the filament, although we have a certain amount of evidence that the rate of damping of these vibrations is influenced slightly by the kind of supports used.

In order to eliminate the noises entirely, the only practicable way seems to be to prevent any vibrations

from reaching the filament from outside. A design of valve holder which achieves this object depends upon the fact that a spiral spring can be made which has a very low natural periodicity for transverse, longitudinal, and torsional vibrations. The valve holder is supported on such a spring and connections are made to terminal points on the base by means of phosphor-bronze springs.

There is no necessity, of course, to use this type of holder when only two stages of audio-frequency amplification are used.

Conclusion.

In concluding this account of the properties of the dull-emitting thoriated filament it may be interesting briefly to compare the efficiency or economy of this type of dull emitter with that of the oxide-coated filaments.

In order to do this, previously published curves * connecting electron emission with power consumed in cathode-heating may conveniently be referred to. H. D. Arnold in his paper states that the customary operating power for the oxide-coated filament is from 8 to 9 watts per cm^2 of cathode surface, and that the range of efficiencies lies between 10 mA of electron emission per watt (of heating power) and 100 mA per watt.

On the other hand, with the thoriated filament this efficiency ranges from 10 mA per watt at 1 630° K. to 200 mA per watt at 1 910° K., and 400 mA per watt at 2 005° K.*

These figures, however, neglect the loss of power in the leads, and the apparent difference between the two filaments is in practice reduced as a result of the increased loss due to the heat conducted away by the filament leads in the case of the thoriated filaments, which operate at a temperature about 500 to 600 degrees higher than the oxide-coated ones. Actual valves of the two types, produced commercially, show practically no difference between the efficiencies of the two filaments, and the results of any rivalry between the two will probably be determined by other factors.

* H. D. Arnold: *Physical Review*, 1920, vol. 16, p. 76.

* S. Dushman: *General Electric Review*, 1923, vol. 26, p. 159.

Discussion before the Wireless Section, 2 April, 1924.

Professor C. L. Fortescue: This paper deals with the only marked new development in the small valves that has taken place during the last seven or eight years, and it is interesting to note that it involves a number of very subtle physical problems. Frequent mention is made of Richardson's work function, and the possibility of reducing this to one-tenth or one-hundredth of its present value by some indirect treatment of the surface of the filament immediately suggests itself. If this were possible the life of the valves might be enormously increased. Two important practical considerations with respect to the dull-emitting filaments are the effects of running at too high a temperature and of working the valves at too high a voltage. With regard to the former, the authors have demonstrated the re-forming of a filament after overheating, and a natural inquiry is whether it is always possible to carry out this process of re-forming after a filament has been damaged by overrunning. So far as the high voltage is concerned this appears to be necessary when working with loud-speakers, and it would be interesting to know what are the limits actually found with the various types of dull-emitter valves and what are the hopes of raising this limit in the near future. The possibility of using these filaments for transmitting valves also suggests itself, and the authors' views on the likelihood of this development would be interesting.

Mr. R. C. Clinker: I am much interested in Fig. 3 in which the difference in the shape of the characteristic curve is shown for both tungsten and thorium emissions. On page 37 of Van der Bijl's book on the "Thermionic Vacuum Tube" an additional explanation is given of the non-saturation effect. It is pointed out that the filament is not a perfect cylinder but is full of protrusions and hollows, the effect of which is to cause large electrostatic fields at the surface. High plate potentials are required to overcome these fields and to pull all the emitted electrons across. Is it not possible that a difference in surface conditions between the pure tungsten and the thorium-coated filament will account for some of the difference shown in Fig. 3? In the section dealing with the life test, the statement is made that the valves are run with a steady a.c. filament voltage of 1·8 and an anode voltage of 50, the grid being connected to one filament lead so that the grid potential virtually oscillates between zero and 1·8 volts positive. I think that the last figure should read 2·5 volts. With regard to microphonic noises and the fact that the dull-emitting filament has a corresponding higher resilience than the high-temperature filament, we have found that if the voltage is raised from 3 to, say, 5, the damping is markedly greater. This can be clearly seen by twanging a stretched wire (as employed by the Royal Aircraft Establishment at Farnborough) tuned to agree with the natural frequency of the filament. The latter is seen to vibrate over a smaller amplitude when operating at the higher temperature. On the other hand this does not appear to reduce noticeably the total microphonic noise in the telephone.

Mr. S. R. Mullard: The result of this work can, I think, be traced back to that period during the war when those who were experimenting with valves were trying to solve the troubles arising from crackling noises occurring in receiving valves. This trouble was ultimately traced to impurities in the filament, and from that stage the information gathered was helpful to valve manufacturers in the production of dull-emitting filaments. Certain transmitting valves in which impure tungsten was used certainly showed this dull-emitting property. I think that Prof. Fortescue had a 250-watt or a 500-watt transmitting valve which gave very good results as a dull emitter. The experience which we have obtained runs almost parallel with the research carried out by the authors, and I think that the future

with dull-emitting filaments lies in an arrangement for damping microphonic noises as shown in the new holder, or in the use of "oxide-coated" filaments, the latter having the advantage of being non-microphonic when used in the standard holder.

Mr. J. F. Herd: I believe that we at the Radio Research Board Station, Aldershot, were actually among the first to be supplied with dull emitters when these were available, as an experimental product, from the company which the authors represent. We were interested in their use in connection with a continuous recorder for atmospherics, working with 7 to 9 filaments burning 24 hours a day and 7 days a week. The advent of the dull emitter gave great promise of a reduction of accumulator maintenance. The valves then supplied were known, I think, as "S.R.1." These were set up and used continuously for 24 hours a day for rather more than 6 months, representing a burning life of 5 000 hours, without any diminution of emission. Only one filament burned out of its own accord. Then, unfortunately, the whole of the 9 filaments were accidentally burned out, and the subsequent batch of production valves which were used to replace them were those referred to in the paper as "L.T.2." With these the stability of emission was much inferior to that of the experimental samples and of those now being supplied. We have at present set up later dull emitters which are giving great satisfaction. In common, I think, with other valve users, I regret to learn from the authors that microphonic noises are more or less inherent to this type of filament. When a 7- or 8-stage amplifier is used, these noises become serious, and in our case might readily give rise to spurious "atmospherics" on a record. We have practically solved that difficulty by means of shock absorbers which protect the amplifier from floor vibrations. One regrettable feature of the dull emitters, as compared with the oxide-coated filaments mentioned by Mr. Mullard, is their comparative fragility. Many users will agree that they are liable to be broken by an accidental knock. They seem to me to be more fragile than an ordinary tungsten filament and certainly much more so than an oxide-coated one.

Mr. E. Y. Robinson: I should first like to refer to the authors' remarks on the contact-potential effects as illustrated in Fig. 2. The shift of the anode characteristic to the right is what one would expect from a consideration of the effect of contact potentials. From the space-charge equations which have been given by various people two formulæ have been evolved, neither of which, in my opinion, represents the true conditions existing in the valve. If we take the current in the valve as I_a, the anode potential as E_a, the grid potential as E_g, the voltage factor as μ and the contact potential as E_c, we have the following formula :—

$$I_a = K(E_a + \mu E_g + E_c)^n$$

The other type of formula is as follows :—

$$I_a = K(E_a + \mu E_g + \mu E_c)^n$$

This second formula is the more correct, and in explaining the reason for this I should like to give my views as to what actually does happen in the valve. In the case of a valve which has a plain tungsten filament and nickel electrodes, then, taking the work function for tungsten to be 4·6 and for nickel to be about 3·6, the application of 100 volts to the plate will give in effect 101 volts on the plate, and 10 volts applied to the grid will give in fact 11 volts on the grid; if a molybdenum grid were employed, 10·2 volts instead of 11 volts would be obtained. Considering, now, the case of a valve having nickel electrodes, if we have 101 volts effective on the anode and 11 volts effective on the grid, and if in place of a tungsten filament we put in a thoriated filament, instead of the 101 volts on the anode we have 99·6, and instead of 11 volts on the grid we have 9·6, so that in effect we shift the anode current and voltage characteristic to this extent. Incidentally we also shift the grid-current characteristic, so that we lose practically nothing. (Actually we lose 1·4 volts on the anode.) That explains the shift of the curve. Now I come to the formula which I think should be employed. It is as follows :—

$$I_a = K\{(E_a + {}_aE_c) + \mu(E_g + {}_gE_c)\}^n$$

where ${}_aE_c$ is the contact potential between filament and anode, and ${}_gE_c$ is the contact potential between filament and grid. Although the adoption of this formula has no practical use since the refinement introduced is far outweighed by such effects as emission velocities, etc., which are not capable of calculation, this type of formula enables us to visualize the operation of contact potentials. There is a certain effect that I have found with oxide-coated filaments which I should like to record. When using an oxide-coated valve as a reacted detector, the circuit being very critically reacted and adjusted so that there was no backlash when it started oscillating, a feature when using certain valves was that the circuit would oscillate for about 5 seconds, then remain silent for a further 5 seconds, then oscillate again for 5 seconds, and so on. Various possible causes, including the presence of gas in the valve, were ruled out by experiment, and I was led to accept the following explanation. In an oxide-coated filament valve the slope of the characteristic curve is very much more dependent on the total emission from the filament than in the case of the ordinary tungsten filament valve. Consequently a small increase of emission will increase the slope of the anode characteristic and thus cause a critically reacted circuit to oscillate. What apparently happens in the case given above is that the work function of the oxide coat—or more possibly of one spot in the oxide coat—changes periodically and thus periodically changes the slope of the anode characteristic. This effect has been observed in several valves both purchased and made by myself, so that it seems to be a common failing. The moral is that oxide-coated valves which are very closely designed as regards emission may prove to be unsuitable for use in critically reacted sets. As pointed out above, the grid-current curve is shifted over to the right of the zero grid voltage. Consequently, when the valve is being employed as a detector using cumulative grid rectification, the grid leak should be connected to the positive terminal of the filament battery in order to bring the grid potential to its optimum value.

Mr. H. W. Edmundson: One point arises with

regard to the dull-emitting filaments as compared with the pure tungsten filaments, and that is the increase in the length of filament which is possible with the former. If one takes two filaments to work on the same voltage, the dull-emitting filament consuming $\frac{1}{4}$ ampere and the pure tungsten $\frac{1}{2}$ ampere, the dull-emitting filament is nearly twice as long as the pure tungsten filament. This enables a lower anode resistance to be used. Valves with dull-emitting filaments are stronger than valves with pure tungsten filaments, even when the dull-emitter filament is smaller in diameter.

Mr. C. F. Phillips: It is to be regretted that in the latter part of the paper the authors confine themselves particularly to their most recent development, the D.E.3 valve. The conclusions set out at the end of the paper relate to dull-emitting filaments in general, whereas a large part of the paper deals only with that specific type of valve. There is a new type of filament known, I believe, as the "XL," or thoriated tungsten, filament with possibly some special addition such as the authors have mentioned. This filament is applied to-day to valves of many different kinds. For instance, a somewhat similar filament to that used in the D.E.3 is applied to a valve which consumes 0·8 ampere at a pressure of 4·5 volts; such a valve has a very large emission, approximately 90 mA. For experiment, two valves were taken consuming respectively 60 and 800 mA in the filament (XL type in each case); as might be expected, the first valve was extremely microphonic, whereas the second was not in the least noisy. It therefore occurs to me that in the desire to make a real dry-battery valve there has been a tendency to go down to the extreme limit, i.e. 60 mA, when perhaps, had the manufacturers endeavoured to make an XL filament valve consuming 100 or 120 mA, we might have got a more advantageous valve for use commercially with dry batteries, as such a valve would be deprived to some extent of its microphonic properties because the filament consumption would lie between the 60 and 800 mA that I have mentioned. I have noticed what seems to me to be an unfortunate fact in connection with valves having oxide-coated filaments. To-day we are most of us interested in that portion of the valve curve which lies to the left of the zero grid line. In a valve with a thoriated filament we can make that portion of the curve extremely long by applying a comparatively high anode potential and maintaining the grid at a suitable negative potential. If we try to do the same thing with an oxide-coated filament the same conditions do not apply, because as we increase the anode voltage above the limits fixed on the box the valve starts to "blue," so that the very valuable portion of the curve to the left of the zero grid line cannot be prolonged.

Mr. P. G. A. H. Voigt: I have had two very poor D.E.R. valves which I ran all night without high tension, and the emission was only normal for 2 minutes. I should like to know whether there are any hopes of restoring the emission of these valves. As Mr. Phillips has said, the negative side of the grid voltage is the one that most interests the wireless user, and I have been applying high tensions (up to 300 or 400 volts) on the anode to increase this side. The authors say that the use of a very high potential depends on the diameter of the bulb. I should like to know whether it is safe to use the L.S.5 valve at 500 volts when it is marked for only 120 volts.

Mr. W. H. Edridge: Previous speakers have emphasized the utility of the left-hand side of the valve plate-current/grid-potential characteristic. Since there can be no doubt that it is the portion of the curve which lies outside the corresponding grid-current curve which should be utilized, I would ask the authors to give further particulars concerning the position of such grid-current/potential curves for the various types of valves which have been examined by them in the course of research and which are alluded to in the paper. The question of admissible plate potential also hinges upon the same question. I should be glad, therefore, if the authors would state whether the limits given for admissible grid potential for various sizes of dull-emitter valves may not be considerably increased if the plate current is maintained at a given figure, for example half the saturation value, by means of negative grid bias. My reason for raising this point is that it would appear possible that the tendency of the valve to lose efficiency when higher plate potentials than those specified by the authors are employed, may possibly be a function of the plate current rather than of the plate potential producing it; that is to say, the detrimental effect of high plate potential may be eliminated by an equivalent negative grid bias. With reference to the fact that these dull-emitter valves appear to be considerably more sensitive to variations of filament current in so far as oscillation is concerned, should this prove to be an objectionable characteristic it would appear to be easy to compensate for it by suitably placing a filament rheostat in the circuit.

Mr. L. S. Harley: I should like to know whether the maximum safe anode voltage, which is stated to be a function of the size of the bulb, does not depend also on the emission from the filament and possibly on the state of cleanliness of the interior surface of the valve bulb. It occurs to me that the limiting voltage may not be quite so definite as is stated in the paper.

Mr. W. F. Marriage (*communicated*): The paper deals primarily, of course, with valves of the thoriated-filament type. The authors refer to the work which has been carried out by the Western Electric Company in the development of valves using oxide-coated filaments. The paper to which the authors refer for information on this latter type of valve (*Physical Review*, vol. 26, p. 76) does not, however, deal with a number of features of considerable importance in valve work, and it will probably be of interest to members to touch briefly upon some of these points. I propose therefore to confine my remarks under four headings: (1) Microphonic noises, (2) Uniformity of production, (3) Stability of emission, and (4) Life.

(1) *Microphonic noises*.—As demonstrated by the authors at the conclusion of the paper, the thoriated tungsten filament is particularly microphonic. The oxide-coated filament, on the other hand, is much less liable to trouble of this kind so that no special precautions are needed in practice as regards light and flexible wiring. This lack of microphonic effect is controlled by

the fact that the oxide-coated filament is made with a special alloy core which is not so highly elastic as thoriated tungsten. Furthermore, the oxide-coated filament is of sturdy dimensions, the dimensions in the case of the "Wecovalve" being 0·0022 in. diameter and in the case of the repeater tube 0·002 in. by 0·012 in. This introduces a greater impedance to movement and makes the oxide-coated filament much less susceptible to vibration. Can the authors supply corresponding figures for similar valves with thoriated tungsten filaments?

(2) *Uniformity of production.*—The emission from thoriated tungsten over the operating range is several times as much per cm^2 as from the oxide-coated filament over its operating range. This greater density of emission from thoriated tungsten has the effect of requiring for thoriated tungsten filament valves a smaller plate and grid structure than is required in the case of an oxide-coated filament valve having the same characteristics. This smaller structure has the disadvantage that slight departures from specifications in assembly cause greater departures from normal tube characteristics. Thoriated tungsten tubes would therefore be expected to be less uniform in characteristics for equal skill in assembly. Uniformity of characteristics are, of course, of very great importance to ensure that when valves are replaced the same performance will result.

(3) *Stability of emission.*—On pages 692 and 693 the authors treat this subject in a very comprehensive manner. Their remarks on anode voltage and degree of vacuum apply, in general, to the oxide-coated as well as to the thoriated tungsten filament. With regard to filament temperatures, however, the thoriated tungsten filament is under the serious disadvantage that, when overrun, its normal emission is changed to that of a pure tungsten filament. The effect of momentarily overrunning an oxide-coated filament is to produce increased emission and to take a few hours off its average effective life, but, unlike thoriated tungsten, the oxide-coated filament returns to its normal stable emission when the filament is reduced to its normal operating temperature. Consequently no inconvenience is occasioned by the necessity of reactivating the filament. With the oxide-coated filament such temporary overrunning does not result in a changed anode impedance when the normal filament current is resumed. It would seem probable that in the case of thoriated filaments the process of rejuvenation would have to be carried out with very great care, and probably by expert hands to ensure that the anode impedance did not differ from its original value. Change of anode impedance will, of course, affect the performance of the valve in the circuit in which it is used, and might result in appreciable distortion due to this changed impedance no longer matching the impedance of the transformer or the circuit to which it is connected.

(4) *Life.*—Reliable data are available on the average life of oxide-coated tubes as used in telephone repeaters, and very extensive tests involving many thousands of this type of valve indicate that the average effective life exceeds 20 000 hours. This life figure covers failure from all causes. It would be interesting if the authors were to give corresponding figures for telephone repeater valves having thoriated tungsten filaments. The life of an oxide-coated filament culminates in a process lasting for a considerable period of time—several hundred hours in many cases. This process begins with the formation of a "bright spot" in the filament which very gradually increases in brightness until the metallic core is fused. The valve is usually in good operating condition throughout this period. The advantage of this behaviour lies in the fact that ample warning is given of the approaching failure and the valve may be replaced while not in actual service. I should like to remark on two points which arose during the discussion. Prof. Fortescue asked whether it was not possible to manufacture a power valve utilizing dull-emitter filaments. In this connection it may be stated that the Western Electric Company manufacture standard valves ranging from 0·05 watt up to 250 watts. These figures represent the safe energy which can be dissipated by the plate. Another speaker made reference to the fact that when the anode voltage for an oxide-coated filament valve was raised above that specified by the manufacturers, blue haze became apparent in the valve. This phenomenon would appear to apply to all types of valve. I should like to say that it does not seem a fair test to overload a valve to obtain increased output: the solution appears to be to obtain a valve which has been designed to cope with the power required.

Messrs. M. Thompson and **A. C. Bartlett** (*in reply*): Prof. Fortescue is probably too optimistic in thinking it possible to reduce the work function to one-tenth or even one-hundredth of its present value. The most electro-positive substance known is probably metallic cæsium, for which Langmuir has obtained the preliminary value of 1·4 equivalent volts for the work function, which compares with 4·5 for tungsten and about 3·0 for thorium.

In the event of a dull emitter being overrun the process of re-forming will generally restore the emission except where the available supply of thorium is consumed, as, for example, at the end of its long life, or where overheating of the other electrodes and of the glass has caused the liberation of electro-negative gases such as water vapour. For those valve users who require a dull emitter to withstand an anode voltage of 300 to 500, the L.S.5 type will be found suitable. The filament of this valve requires about 0·8 ampere at 4·5 to 5 volts, the total emission being 60 to 100 mA. This valve will also allow an anode dissipation of 15 watts.

In reply to Mr. Clinker, the saturation part of the characteristic curve is very nearly flat for the ordinary tungsten filament, while there seems to be no reason why a dull-emitting filament should have either larger or more numerous hollows in its surface than ordinary tungsten. The figure of 1·8 for the virtual oscillating grid voltage during the life test is of course the R.M.S. value.

In reply to Mr. Herd, our experience is that with filaments of the same dimensions the dull emitter is stronger throughout its life than an ordinary tungsten filament. This advantage is the result of the fact that, at the operating temperature of dull emitters,

crystal growth, which sometimes gives rise to the well-known "off-setting" in hot tungsten, does not take place.

Mr. Phillips is, we believe, under a misapprehension in thinking that the D.E.3 valve received more than its fair share of attention in the paper. If one type of valve is dealt with more than another it is probably the 1·8-volt L.T.1 (or D.E.R.) type. The suggestion that a filament consuming 100 to 120 mA would be better for the D.E.3 valve should perhaps be referred to the dry-battery experts. Three filaments each consuming 60 mA are already a heavy load for the present-day dry batteries, and four such filaments are almost more than they can deal with.

Mr. Edridge suggests that the stability of thorium emission might be almost independent of anode voltage provided the anode current were kept constant by a suitable grid-voltage bias. We can only state that this is contrary to our experience and that, in addition to the mere heating effect of anode power dissipation, there is an additional effect due to the electrical field. The actual value of the safe anode voltage does, of course, vary in valves of the same type, probably as a result of variations in the state of the bulb surface. It is mentioned in the paper that the grid characteristic undergoes a shift similar to that of the anode characteristic. It is therefore possible for the grid voltage of a dull emitter to have a higher positive value than in the case of the hot tungsten filament.

Mr. Marriage gives dimensions of oxide-coated filaments. Corresponding dimensions for thoriated filaments are as follows:—

D.E.3 valve	0·0007 in. diameter.
D.E.R. valve	0·0023 in. diameter.
Repeater valve	0·0035 in. diameter.

We find that under works conditions the proportion of rejected dull-emitter valves manufactured in accordance with close specifications is very small.

It should not be understood that a small amount of overrunning is injurious to thoriated filaments. All types, for example, will easily withstand for lengthy periods a filament voltage 30 per cent above the value at which the valve operates efficiently, and this should be a sufficient margin for the most careless user. One source of trouble may well consist in this, that when the over-voltage is considerably greater than that mentioned above, the filament refuses to melt, as would be the case if the oxide-coated filament were similarly overloaded, so that the user does not acquire sufficient respect for the properties of the filament.

With regard to the life of repeater valves, it is only a little more than a year since the Marconi-Osram works began to manufacture a dull-emitter type of valve. Our life tests have therefore lasted only about 8 000 hours, but, judging from the shape of the curves, we see no reason why the performance of the oxide-coated type should not be at least equalled. We might also mention that with other types of thoriated dull emitters, lives exceeding 20 000 hours have been recorded in actual operation.

In conclusion, reference should be made to two recent developments—both due to the General Electric Company of America—in the technique of dull-emitter manufacture. Visible evidence of one of these developments is afforded by the silvery appearance of the bulb in most modern dull emitters. The silvery film consists of magnesium, which assists in producing a perfect vacuum in much the same way as phosphorus assists in producing the vacuum in lamps.

The second development is outlined in E.P.184 446, which describes the introduction of carbon into a thoriated tungsten filament, as a result of which thorium emission becomes less sensitive to the action of electro-negative gases present in the valve atmosphere. The oxidation of the thorium atoms lying on the surface of the filament is counterbalanced by the reducing action of adjacent carbon.

SOME RADIO DIRECTION-FINDING OBSERVATIONS ON SHIP AND SHORE TRANSMITTING STATIONS.*

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[From the National Physical Laboratory; communicated by permission of the Radio Research Board.]

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SUMMARY.

An account is given of some experiments conducted with two direction-finding receiving stations taking observations on ship transmitters located at various positions in the North Sea between England and the Continent. Damped waves of length 450 m were employed, as given by the ordinary spark transmitting sets with which the ships were fitted. The results obtained are analysed in detail and the various errors encountered are described. The effect of the various local errors to which a direction-finder is subject is not, however, studied in any detail, the object being rather to examine conditions prevailing across the sea, as compared with those across land. By careful attention to certain details various sources of error present in the earlier experiments were eliminated, with a resultant improvement in the overall accuracy. The general conclusion drawn from the experiments is that when the path of transmission is entirely over sea and in a direction making an appreciable angle with the coast line so as to be free from coastal refraction effects, the accuracy of radio direction-finding is sufficient for many navigation purposes up to ranges approaching 100 miles. Observations taken on various land stations with spark transmitters on wave-lengths of 450 and 600 m show that for greater distances over sea the variable "night" errors encountered are of a much higher order. When the propagation of the waves is entirely over land the corresponding variations are encountered at shorter distances.

1. INTRODUCTION.

Since the early part of 1922, an organization of 10 direction-finding stations under the auspices of the Radio Research Board has been engaged in the accumulation of data on the variations of the apparent bearings of fixed transmitting stations. These stations have worked on the comparatively long waves from 2 km upwards, utilizing the transmissions from the European medium-power and high-power stations. Towards the end of 1922 it was decided to extend the investigation to shorter waves down to 450 m. For this purpose only two stations were employed, one installed at the Slough station of the Radio Research Board, and a second station at Orford which was rented from the Admiralty for the experiments.

With the commencement of operation of the Orford station it was proposed to take the opportunity of studying direction-finding conditions when the propagation was entirely over sea for varying distances. The co-operation of the authorities of the Great Eastern Railway Company made this possible by permitting the transmission of special signals by the Company's ships passing between England and the Continent. Experiments were commenced in October 1922 and continued at various periods until their conclusion in November 1923. The present paper is a descriptive summary of the results and experience obtained during this part of the main investigation and is considered particularly from this point of view of the application of direction-finding at shore stations to the navigation of ships at sea.

2. THE DIRECTION-FINDING STATIONS AND PERSONNEL.

At the Orford station a standard type of Bellini-Tosi direction-finder was used as supplied and erected for the Admiralty by Marconi's Wireless Telegraph Co. The aerial loops were of an approximately diamond shape, supported on a central mast 92 ft. high and four corner masts 32 ft. high, the horizontal span of the loops being 120 ft. On the wave-length of 450 m employed in these experiments the loops were used in the untuned condition, being connected directly to the field coils of the radiogoniometer, with the mid-point of these coils earthed. The goniometer was of the tightly-coupled type and its search coil was connected to the primary coil of an intermediate circuit and tuned with a variable air condenser. The secondary coil of this circuit was tuned with a second condenser, leads from which were taken directly to the amplifier. In the initial experiments a single stage of high-frequency amplification with tuned anode and grid circuits was employed, followed by a detector valve and two or three stages of note magnification. At a later date this was replaced by a standard type of 7-valve high-frequency amplifying detector followed by two stages of note magnification. With these arrangements wireless bearings were usually obtainable on ship and shore transmitting stations with an angle of swing at the minimum down to 1°, i.e. the angle at the minimum over which no change in signal strength can be observed. Although the sensitivity of the 9-valve receiver was such that loud signals were frequently obtained on the intermediate circuit with the aerial loops disconnected, no diminution of this angle of swing was ever obtainable by a reduction in the sensitivity.

At Slough the set was also of the Marconi-Bellini-Tosi type similar to that of Orford but of a more temporary nature, particularly in the matter of mast construction. The set was of the portable land-station type as formerly used by the British Army, with triangular aerials sup-

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ported on a 70-ft. central mast, and a horizontal span of 200 ft. The receiving arrangements were otherwise identical with those at Orford, with the exception that the whole hut containing the apparatus and the operator was screened with a lining of wire netting of 1-inch mesh. Measurements within such a screen have shown that the strength of an incoming electromagnetic wave is reduced to about 5 per cent of its value outside the screen.* This resulted in the practical elimination of all direct pick-up of signal on the intermediate and amplifier circuits, with the 9-valve receiver working at its highest sensitivity, and a ship's type of spark transmitter operating at a distance of about 11 miles.

The two direction-finding stations were run under the personal supervision of the author, who took an active share in all the observations made. The bulk of the observations were, however, made by the author's assistants, each of whom is highly skilled in this direction, as a result of a large amount of direction-finding observation work carried out during the past two or three years.

3. Duration and Procedure of Experiments.

The first tests made on special transmissions from the boats of the Great Eastern Railway Co. were carried out during the two weeks commencing the 9th October, 1922. On a somewhat extended scale the experiments were resumed on the 12th February, 1923, and continued intermittently until the 15th November, 1923, at which date the experiments were concluded, after a total period of nearly 14 weeks' nightly observations had been worked.

The general procedure adopted during this work was briefly as follows: As each of the various ships approached one of the light vessels or light buoys on its route to or from the Continent, the wireless operator, being warned by the navigation officer, made a preliminary call to Orford. After receiving the reply from Orford, the ship's operator sent a special code signal for a period of about 1½ minutes to enable the observers at Orford and Slough to make simultaneous determination of the wireless bearings of the ship. Direct and reciprocal readings on the goniometer scale were always taken and the mean of these (with the appropriate 180° correction) was taken as the observed bearing. At the time of sending of the special signal the ship's navigation officer recorded the ship's position, as estimated by distance and compass bearing from the light vessel. The above procedure was repeated for each ship on passing each light vessel or buoy, the code signal used in the transmission being sufficient for identification purposes in the recorded readings. At the conclusion of each week of the experiments the log sheets from the ships and from the direction-finding stations were sent in independently to the National Physical Laboratory. With the unavoidable exception of the author, the direction-finding observers were purposely kept uninformed as to the positions of the ships, the operators of which also knew nothing of the conditions or results at the direction-finding stations. These precautions, together with the prohibition of any communication between the operators on ship and shore, permitted the reception of absolutely unbiased results.

In the majority of the experiments the period of working was from 2245 to 0400 G.M.T., use being made of that portion of the passage of the two outward-bound and the two inward-bound boats which fell within this period. In practically every one of these cases darkness prevailed throughout the whole test. During the summer, however, when the schedule times of the boats were altered to British summer time, the periods worked were 0100 to 0700 G.M.T., to observe the effect of sunrise and subsequent daylight.

In addition to the above special signals sent from the ships, transmissions were made at intervals during each observation period by the Great Eastern Railway Co.'s station at Parkeston Quay, the National Physical Laboratory's station at Teddington, and (for the use of the Slough direction-finding observer only) by the Orford station. This arrangement was made to enable a comparison to be effected between the direction-finding observations taken on the ship stations and those taken during the same periods on land stations over distances of the same order.

In entering the readings on the observation sheets for both ship and shore stations, the observer recorded his opinion as to the reliability of the observation as judged from the nature of the signal minima. As previously noted, bearings on signals of adequate strength could be observed with an angle of swing of 1° to 2°, and under favourable conditions this angle was not greater than 8° in observing at Slough on signals transmitted by a ship on the far side of the North Sea over a distance of nearly 200 miles. In many cases, however, this angle was necessarily much larger, due to the adverse conditions experienced, the most prominent of these being interference, flat minima and wandering minima.

The two latter were very frequent in some portions of the test and were characterized first by a signal audible all through the minimum, but the strength of which gave no detectable change over an angle sometimes amounting to 90°; and secondly by a drift of the minimum at a varying rate round the goniometer scale. Although no really hard-and-fast rule can be given to observers to determine the reliability of observations, it is in general not considered that accurate bearings can be obtained when the angle of swing is greater than about 20°.

When observing on the ship transmitters at Orford the signal minima were always steady, apart from the drift due to the actual motion of the ship, when transmitting at short ranges. Although the minima in some cases had become appreciably flattened, and the observations were accordingly marked "unreliable," the results given in Table 1 show that the corresponding error in bearing was usually quite small.

4. Discussion of the Results obtained.

During the whole period of these experiments the total number of observations taken on the ships' transmissions was 996, and an additional 3 444 observations were made on the transmissions from the land stations. A summary of all the results is given in Tables 1 to 8, and these are discussed in detail in the present section.

* R. H. Barfield: "Some Experiments on the Screening of Radio Receiving Apparatus," *Journal I.E.E.*, 1924, vol. 62, p. 257.

From the various ships' positions recorded on the respective log sheets, the true bearings of the ships at both Orford and Slough were obtained from charts, each case being worked out individually. The true bearings so obtained were compared with the observed wireless bearings, and the difference between these is termed the "error" in the following tables. It will be noted that in some cases the results are divided into the two classes "Reliable" and "Unreliable" in accordance with the notes made by the observers of the wireless bearings. This classification does not necessarily indicate that the bearings are inaccurate. In 46 cases no bearing was obtainable on the ships at Slough, on account of the absence of any detectable minimum of signal strength for the whole rotation of the goniometer search coil.

(a) *Ships' transmissions.*—Table 1 gives a summary of all the observations made (at Orford and Slough) in the form of numbers and percentages of bearings with varying errors. Considering first the observations at Orford, it will be seen that there is little difference in the percentage of the errors of the bearings marked "reliable" and "unreliable." Over 87 per cent of the bearings in each class are correct within 3°, while the maximum errors are 7·6° and 9·3° respectively for the two classes. Referring to the observations made simultaneously at Slough, however, it will be seen that while the percentage (83·8) of those in the reliable class which are correct within 3° is a little less than the corresponding figure for Orford, the majority (57 per cent) of the unreliable readings at Slough are more than 3° in error. The largest errors recorded at Slough are also much greater than those at Orford.

From these considerations it may be concluded at once that while, for the observations at Orford, the observer's opinion as to the reliability of the reading was no criterion of its probable accuracy, at Slough the observer was able, to a limited extent, to detect and condemn those readings which were more seriously in error.

A detailed consideration of the results as observed on the ships while passing the various light vessels and buoys shows that the errors are practically of the same magnitude for each position, although the actual extreme values are much greater at Slough than at Orford. The systematic error involved in taking bearings on ships in the various positions is not greater than 1° in the majority of cases and is thus comparable with the limit of accuracy of the direction-finders. In the case of the Shipwash and Sunk light vessels, however, the error amounts to 2°. It was thought at first that this might be a permanent local error of the direction-finding installation, due possibly to coastal refraction. Considerations of the directions of the above light vessels relative to Orford on the chart reproduced in Fig. 1, shows that the waves transmitted from these positions would cross the coast at only a small angle to the normal, and the possibility of any appreciable refraction is therefore remote. Furthermore, it will be seen that signals arriving from positions at the Outer Gabbard and Longsand in closely related directions to those from the Shipwash and Sunk, respectively, are subject to a

TABLE 1.

Summary of all Observations obtained.

Error in bearing	At Orford				At Slough			
	Observers' remarks on observations				Observers' remarks on observations			
	Reliable		Unreliable		Reliable		Unreliable	
	Number	Per cent	Number	Per cent	Number	Per cent	Number	Per cent
Up to 1°	201	43·8	46	42·6	61	34·1	25	12·2
1°–2°	116	25·2	32	29·6	47	26·2	39	19·1
2°–3°	84	18·3	16	14·8	42	23·5	23	11·3
3°–4°	28	6·2	8	7·4	10	5·6	24	11·8
4°–5°	22	4·8	2	1·9	4	2·2	20	9·8
5°–10°	8	1·7	4	3·7	13	7·3	39	19·1
Over 10°	Nil	Nil	Nil	Nil	2	1·1	34	16·7
Total ..	459	100·0	108	100·0	179	100·0	204	100·0
Largest error recorded ..	7·6°	—	9·3°	—	12·2°	—	33·8°	—

very reduced systematic error. Since the ships' positions were estimated from the light vessels, the accuracy of the true bearing depends upon the accuracy of their charted positions. It is understood from the Trinity House authorities that the possibility of these charted positions being incorrect is somewhat remote. Such inaccuracies are not unprecedented, however, for three cases were brought to notice recently as a result of radio-acoustic experiments carried out in the English Channel.* One of these light vessels, the West Hinder, was found to be $1\frac{1}{2}$ nautical miles out of its charted position. Such increase in distance, however, suggests that some at least of the errors arise from some uncertainty of the knowledge of the ships' positions from which the true bearings are obtained. In the last column of Table 2 are given the values of the error in the position which correspond to a 2° error in bearing at Orford, and from these it is seen that for the positions closer than the Galloper it is necessary that the ship's position recorded be correct within 1 mile, and that at the Shipwash light vessel an accuracy of $\frac{1}{3}$ mile is required. Now whereas under favourable conditions the estimated

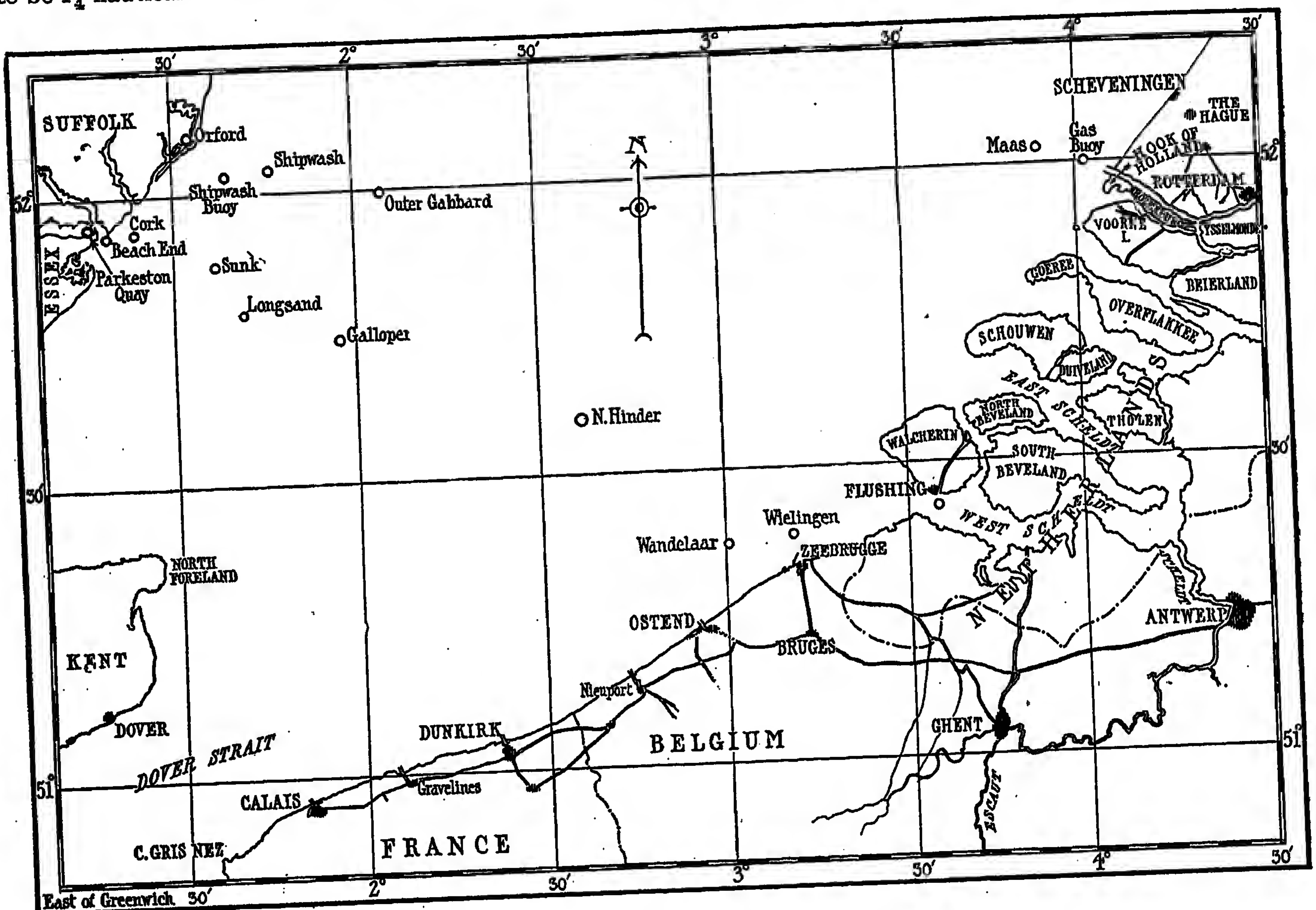

FIG. 1.

an error in the case of either Shipwash or Sunk would produce a change in bearing at Orford of several degrees.

Table 2 gives an abstract of the results in the form of the numbers and percentages of the observed bearings whose errors are not greater than 2°. These figures show generally that as the distance from the ship to Orford increases, the proportion of the results correct within 2° increases from about 45 per cent to 90 per cent.

The relation is not a strict one in view of the high percentage accuracy obtained at the Cork position, and it is also to be remembered that compensation for the systematic errors discussed above would greatly increase the percentages corresponding to the Shipwash and Sunk positions. The general increase in accuracy with position is well within such a limit of accuracy, various circumstances arose in these experiments which might considerably increase the difference between actual and recorded positions. Among these circumstances were the prevalence of bad weather, mist, etc., which made a visual estimate of distance uncertain, and some unavoidable delay between the determination of the position and the transmission of the special wireless signal; while on some occasions interference prompted the observer at Orford to request a repeat signal, from a fresh position of the ship which was not always corrected. It should also be noted that all observations were made while the ships were travelling at a speed in the neighbourhood of 20 knots, and that at a short range such as from the Shipwash the motion of the ship during the transmission of the $1\frac{1}{2}$-minute signal corresponds

* A. B. Wood and H. E. Browne: "A Radio-Acoustic Method of Locating Positions at Sea," *Proceedings of the Physical Society*, 1923, vol. 35, p. 189.

TABLE 2.

Numbers and Percentages of all Bearings up to 2° in Error, observed at Orford on Ships at the Various Positions.

Position of ship	Approximate distance from Orford	Errors in bearing 0°–2°		Error in ship's position corresponding to 2° error in bearing
		Number	Per cent	
	miles			miles
Shipwash ..	11·0	24	44·5	0·36
Cork	12·5	76	68·5	0·45
Sunk ..	16·0	27	49·0	0·56
Longsand ..	21·5	18	58·0	0·71
O. Gabbard ..	24·0	31	61·0	0·80
Galloper ..	30·5	64	82·0	1·00
N. Hinder ..	58·0	72	80·0	1·67
Wielingen ..	87·0	66	85·5	2·86
Maas ..	102·0	18	90·0	3·34
All positions..	Various	396	70·0	—

to a change in bearing at Orford of about 3°. This drift in the observed bearing was very noticeable, but the mean of the direct and reciprocal readings gives the only average value which can be used. This point is one which must frequently arise in the commercial use of direction-finding at short distances, and is partially avoidable by decreasing the duration of the transmission and observing the bearings as quickly as possible, in the manner adopted in the special tests to be described later.

The general result of this analysis of the observations taken at the Orford station is therefore that under ordinary working conditions at sea, wireless bearings can be obtained on ships at distances up to about 100 miles across open sea to an accuracy such that over 80 per cent are correct within 2°, and that the frequency of occurrence of an error of more than 5° is such as to be negligible for practical working. What may be termed "incipient night effect" was evidenced at the longer ranges by flatness of minima, but no error of any magnitude due to this cause has been experienced.

The words "across the sea" must be understood to exclude the case in which the transmission is in a direction making a small angle with the coast line, resulting in coastal refraction effects. In a similar manner the effect of waves crossing cliffs, or being subject to any other disturbance at the direction-finding receiver, are excluded from the above statement of observed results.

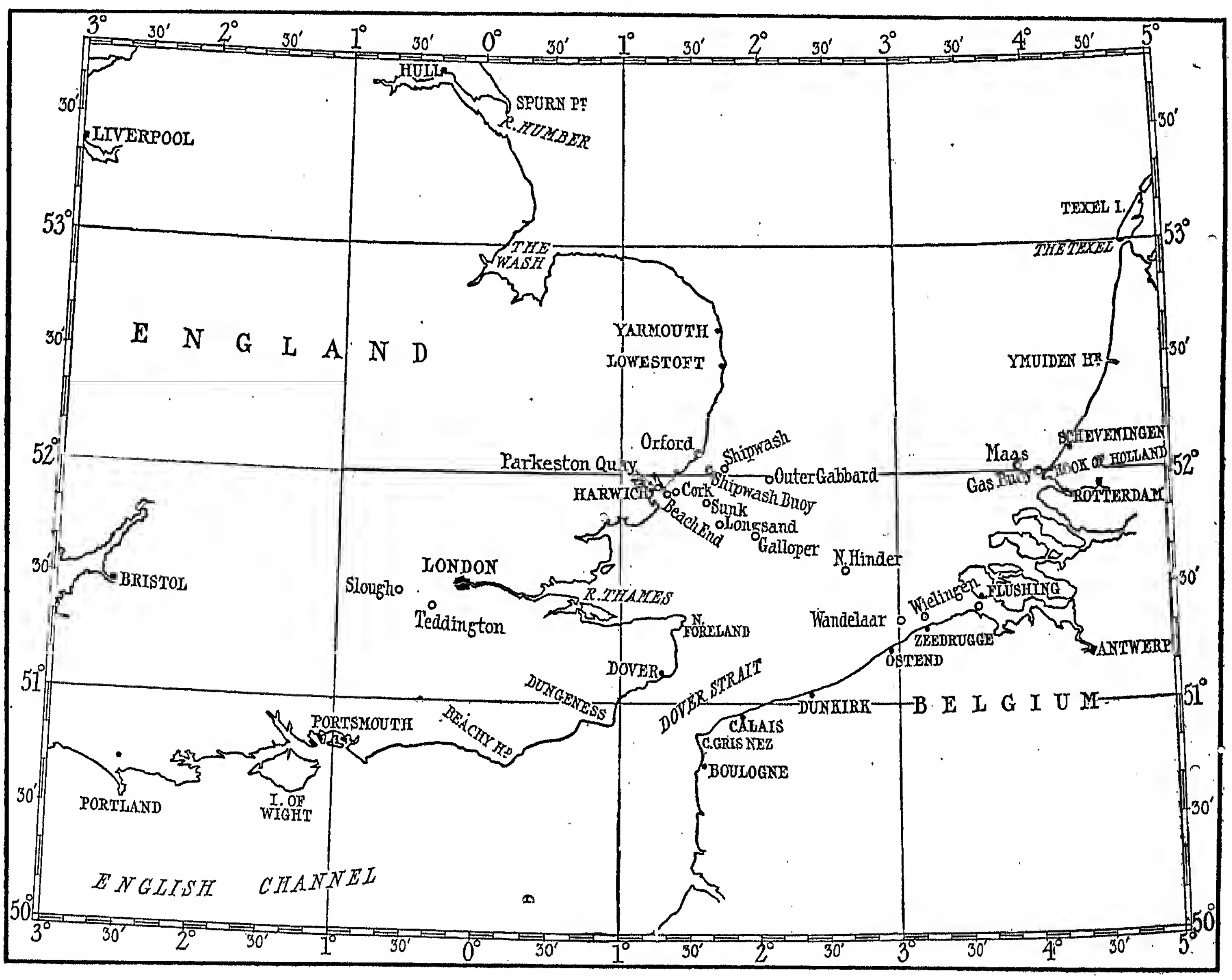

FIG. 2.

At the Slough station the night effects were very much more prominent in the way of extreme flatness of minima and large errors in observed bearings ranging up to nearly 34°. As demonstrating the accuracy which is obtainable in the absence of these night conditions, Table 3 gives a summary of all the observations taken on the ships at various times after sunrise. Nearly 77 per cent of the reliable readings were correct within 2°, these being taken at distances ranging from 89 up to 191 miles (see Fig. 2). At the Maas light vessel at a distance of 191 miles from Slough, 8 of the 9 readings obtained were within 2°, the remaining reading being − 2·2° in error.

(*b*) *Transmissions from land stations.*—In Table 4 is given a summary of the results obtained during these experiments in making direction-finding observations on the three land stations employed for the purpose. The spark transmitting set at each station was employed and the wave-length of 450 m was used throughout.

TABLE 3.

Summary of all Observations taken after Sunrise, at Slough.

Error in bearing	Reliable: Number	Reliable: Per cent	Unreliable: Number	Unreliable: Per cent
Up to 1° ..	23	33·3 } 76·8	—	—
1° to 2° ..	30	43·5 }	1	33·3
2° to 3° ..	14	20·3	—	—
Over 3° ..	2	2·9	2	66·6
Total	69	100·0	3	100·0

As previously mentioned, the majority of the work was done at night, but the day readings tabulated are those taken in the portions of the observation periods which were more than one hour after sunrise. The results given are typical of those which may be observed at any direction-finding station when working at comparable distances and when the path of transmission is partly or wholly over land.

Where the distance is comparatively short, as in the cases of Parkeston Quay to Orford and Teddington to Slough, no difference by day or night is found in the accuracy of the observed bearings or in the sharpness of the minimum signal readings. In the absence of any interference the angle of swing at the minimum is from 1° to 2°, and the mid-position can usually be determined to about 0·2°. Under such conditions quite definite variations in the observed readings are experienced which, however, have a maximum amplitude of about 3°, corresponding to a maximum difference from the mean of about 1·7°, and Table 4 also shows that in less than 2 per cent of cases is the difference greater than 1°. In the two cases quoted there is a permanent deviation of the mean observed bearing from the true value, of over 3°. In the case of Parkeston Quay to

TABLE 4.

Summary of Observations made on Fixed Shore Stations during Experiments with Ships.

Transmitting stations	Observation station	Distance of transmission	Period of Observation	Observations possible	Observations obtained	Mean bearing	Error of mean	Total variation	Maximum variation from mean	Cause of missed observations: Absence of minimum No.	Absence of minimum Per cent	Wandering bearing No.	Wandering bearing Per cent	Interference No.	Interference Per cent	Variations from mean: Up to 1° No.	Up to 1° Per cent	Up to 2° No.	Up to 2° Per cent	Up to 5° No.	Up to 5° Per cent
		miles				degs.	degs.	degs.	degs.												
Parkeston Quay	Orford	16·5	Day	105	105	227·5	− 3·0	3·0	± 1·5	—	—	—	—	—	—	103	98	105	100	—	—
Parkeston Quay	Orford	16·5	Night	386	386	227·4	− 3·1	3·0	+ 1·6	—	—	—	—	—	—	381	99	386	100	—	—
Teddington ..	Orford	93	Day	161	153	237·3	− 3·3	4·0	+ 2·2	1	0·7	—	—	7	4·0	134	83	153	95	—	—
Teddington ..	Orford	93	Night	672	163	238·0	− 2·6	47·0	+ 24·0	365	54·5	101	15	43	6·5	92	13·7	123	18·3	144	21·5
Orford ..	Slough	93	Day	166	155	63·3	− 1·5	4·5	− 2·3	—	—	—	—	11	6·6	112	60·2	153	92·2	155	93·5
Orford ..	Slough	98	Night	647	369	61·0	− 4·3	65·0	− 36·0	171	26·5	50	7·7	57	8·8	23	3·6	69	10·7	244	37·7
Parkeston Quay	Slough	83	Day	105	105	67·5	+ 0·3	2·5	− 1·5	—	—	—	—	—	—	98	93·5	105	100	—	—
Parkeston Quay	Slough	83	Night	400	353	67·1	− 0·1	23·0	− 12·6	31	7·7	4	1·0	12	3·0	259	64·8	303	75·7	329	82·2
Teddington ..	Slough	11·5	Day	167	167	120·1	+ 3·6	1·6	∓ 0·9	—	—	—	—	—	—	167	100	—	—	—	—
Teddington ..	Slough	11·5	Night	635	633	120·3	+ 3·8	2·6	+ 1·7	—	—	—	—	2	0·3	623	99·0	633	99·7	—	—

Orford this is possibly due to coastal refraction, since the path of transmission is in this case nearly parallel to the coast line for a considerable distance (see Fig. 1). It will be observed that the permanent error from Teddington is also about 3°, and other observations show that when receiving at Orford in the sector of approximately 220° to 240°, a correction of + 3° must be made to the observed wireless bearings.

In the case of Teddington to Slough, the cause of the error is obscure and is still under investigation. Replacement of the Bellini-Tosi installation by a portable frame-coil direction-finding set has shown that the error is not due to the apparatus, and an exploration of the neighbourhood has shown that the error varies rapidly with change in position; this indicates that the cause is a very local one.

Reverting to the results given in Table 4, it will be noted that for the greater ranges of transmission (83 to 98 miles) the observations obtained by night differ greatly in several respects from those obtained by day. In the first case, whereas practically all the readings obtained in the daytime were marked reliable, only a few being missed due to interference, a large proportion of the night readings obtained were classed as unreliable, due principally to the flatness of the minima. Secondly, the variations in observed bearings at night were very much more noticeable than in the day, the extreme magnitude of these being 65° by night as against 4·5° by day. Thirdly, in a large proportion of cases bearing observations were impossible at night, due either to the extreme flatness of the minimum signal or to the rapidity with which the apparent bearing was wandering about. For example, of the transmissions from Teddington observed at Orford, in 69·5 per cent of cases no definite indication of the bearing could be obtained during the period of the special signal (1½ minutes) whereas perfectly good bearings were being obtained on the same transmissions at Slough. At the latter station bearing observations on Orford were impossible in 34·2 per cent of cases, due to the prevailing night-effect conditions. These phenomena were experienced nearly every night and the extreme cases were quite frequently encountered in which no variation in signal strength was experienced for a complete rotation of the goniometer search coil, this signal at night often being much stronger than that observable in the daytime in the maximum position.

When it was realized that the accuracy of the results obtained in transmission from the ships was of a high order, several weeks' observations were carried out at Orford on the coast transmitting stations which, with the exception of North Foreland, are on an open sea path from the direction-finding station. The majority of these observations were made on the 600-m wave, and a summary of the results is only given in Table 5 for comparison purposes.

Although North Foreland is the nearest of the stations the path of the waves to Orford scarcely comes within the scope of the term "open sea," since it involves considerable tracts of sandbanks at the mouth of the Thames. For practical purposes the transmission is therefore over land for a portion of the distance and as a result it is seen that while a maximum error of 10·4°

TABLE 5.—*Summary of Observations made at Orford on Fixed Coast Stations.*

Transmitting station	Wave-length	Distance of trans-mission	Period of observation	Observa-tions possible	Observa-tions obtained	Mean bearing	Error of mean	Total variation	Maximum variation from mean	Observations missed through absence of minima		Variations from mean: Up to 1°		Up to 2°		Up to 5°	
										No.	Per cent	No.	Per cent	No.	Per cent	No.	Per cent
	metres	miles				degs.	degs.	degs.	degs.								
N. Foreland ..	600	49·5	Day	380	380	184·6	− 1·2	5·5	− 3·1	—	—	353	94·0	379	99·7	380	100·0
N. Foreland ..	600	49·5	Night	402	392	184·6	− 1·2	15·0	+ 10·4	10	2·5	340	84·5	351	87·6	376	93·5
Dunkirk ..	450	83	Day	294	294	154·5	+ 0·4	3·0	± 1·5	—	—	290	99·4	294	100·0	—	—
Dunkirk ..	450	83	Night	193	186	155·0	+ 0·9	32·0	+ 20·0	7	3·6	163	84·5	174	90·2	183	94·8
Dunkirk ..	600	83	Day	90	90	154·5	+ 0·4	2·0	± 1·0	—	—	90	100·0	—	—	—	—
Dunkirk ..	600	83	Night	86	77	154·4	+ 0·3	15·0	− 9·4	8	9·3	69	80·3	73	84·8	76	88·3
Ostend ..	600	84	Day	313	312	135·3	+ 0·1	4·0	+ 1·7	1	0·3	303	96·8	312	99·7	312	99·7
Ostend ..	600	84	Night	236	196	135·3	+ 0·2	24·0	+ 13·7	40	16·9	161	68·3	164	69·5	180	76·3
Flushing ..	450	98	Day	936	936	116·7	+ 0·7	4·0	+ 2·3	—	—	870	93·0	933	99·7	936	100·0
Flushing ..	450	98	Night	173	147	116·6	+ 0·6	30·0	− 16·6	26	17·7	88	59·8	123	83·7	145	98·7
Scheveningen	600	117	Day	110	110	89·7	− 0·5	6·5	+ 3·8	—	—	100	91·0	109	99·0	110	100·0
Scheveningen	600	117	Night	52	39	88·1	− 1·2	25·0	− 13·1	13	25·0	11	21·1	18	34·6	25	48·1

occurs, over 87 per cent of the observed bearings are within the 2° limit. The nearest of the remaining four stations is over 80 miles from Orford, so that although the transmission is entirely over sea the errors in bearings observed are increasingly larger and the proportion of those less than 2° in error becomes appreciably less. As the distance becomes greater there is an increase in the frequency of the usual night effects as shown by the variations in the observed bearings and the proportion of observations missed owing to the absence of any signal minimum.

In the case of Scheveningen, at a distance of 117 miles, less than half the observed bearings are within the 5° limit of error.

The observations made on the two wave-lengths of Dunkirk, viz. 450 and 600 m, do not show any striking difference. These results obtained on fixed coast stations therefore support the conclusion that 80 to 100 miles is the maximum reliable distance for wireless direction-finding when working entirely over sea.

5. Results of Final Tests.

With the benefit of the experience gained during the experiments above described, two special tests at the Orford station were arranged in October and November 1923, in which every effort was made to reduce to the minimum all the errors which had previously been encountered or suspected. At the invitation of the Great Eastern Railway Co., the author was privileged to be on board the two ships participating in the test to supervise the transmission of the special signals and observe the conditions under which ships' positions were determined. Two tests were carried out on return journeys to the Hook of Holland and Antwerp respectively. During each of these tests, after the first communication had been established with Orford all preliminary wireless procedure was dispensed with, and as the ship passed abreast of each of the selected marks en route the special signal was transmitted for a total period of 1 minute only. By adopting this procedure it was possible to reduce to the minimum all delay and consequent error due to the motion of the ship.

On the journey to and from the Hook of Holland, the selected buoys and light vessels from which transmissions were made were passed, with one exception, within 200 yards and several of them within 100 feet. Conditions were as far as possible arranged so that the ship passed abreast of the mark at about half-way through the special signal, but accurate time records were kept to enable corrections to be made for the drift of the ship during the transmissions, the speed of the ship in this test being 18 knots in the open sea.

Table 6.

Results obtained in a Special Direction-finding Test made at Orford with s.s. "St. Denis" on a Return Journey to Hook of Holland, 15–17 October, 1923.

Date	Time	Position of ship	From Orford				Remarks
			Distance	True bearing	Observed bearing	Error	
			miles	degs.	degs.	degs.	
Outward Journey.							
15/10/23	2202	Parkeston Quay	16·5	230·5	230·3*	− 0·2	W/T D.F. readings very good; angles of swing less than 5°
15/10/23	2254	Guard Buoy	15·0	228·8	228·0*	− 0·8	
15/10/23	2303	Beach End Buoy	15·0	222·4	222·3*	− 0·1	
15/10/23	2317	Cork L.V. ‡	12·5	210·6	211·0	+ 0·4	
16/10/23	0000	Shipwash Buoy	6·5	143·8†	143·7	+ 0·9	
16/10/23	0020	Shipwash L.V.	11·0	117·0†	116·5	− 0·5	
16/10/23	0102	O. Gabbard L.V.	24·0	101·2	102·3	+ 1·1	
16/10/23	0509	Maas L.V.	102·0	92·0	92·5	+ 0·5	Unreliable readings; minima flat and angles of swing 35°–90°
16/10/23	0528	Gas Buoy	108·0	91·8	92·5	+ 0·7	
Inward Journey.							
16/10/23	2313	Hook of Holland	113·0	93·1	94·0	+ 0·9	Unreliable readings; minima flat and angles of swing 25°–60°
16/10/23	2338	Gas Buoy	108·0	91·8	92·5	+ 0·7	
16/10/23	2357	Maas L.V.	102·0	92·0	92·5	+ 0·5	
17/10/23	0344	O. Gabbard L.V.	24·0	108·1	108·3	+ 0·2	All readings reliable and very good; angles of swing less than 5°
17/10/23	0424	Shipwash L.V.	11·0	116·0†	116·5	+ 0·5	
17/10/23	0442	Shipwash Buoy	6·5	145·9†	145·5	− 0·4	
17/10/23	0519	Cork L.V.	12·5	211·2	211·7	+ 0·5	
17/10/23	0532	Beach End Buoy	15·0	221·7	222·0*	+ 0·3	
17/10/23	0543	Guard Buoy	15·0	228·8	228·0*	− 0·8	
17/10/23	0604	Parkeston Quay	16·5	230·5	231·0*	+ 0·5	

* Wireless bearings corrected by + 3° to compensate for direction-finding station error.
† Charted bearing corrected by + 2° to compensate for constant error experienced at these positions. ‡ L.V. = Light vessel.

The first observation was taken during the preliminary communication, while the ship was alongside Parkeston Quay, and, as in the case of observations on the land station at the Quay, a correction of + 3° is necessary to make the observed bearing agree with the true value. A similar correction was also made for the observations taken on the ship at two buoys between the Quay and the mouth of the river.

In Table 6 a correction of — 2° has also been applied to the bearings taken when the ship was passing the throughout and, although fine weather was experienced, the sky was overcast on the outward journey. An average speed of a little over 17 knots was maintained by the ship. The route in this case did not lie so close to the lighted marks, the distance of which varied up to 3 miles. This distance was, however, obtained by the "four-point bearing" method, using the ship's magnetic compass, the distance run being recorded on the ship's log. The results obtained are given in Table 7 and, as before, corrections have been applied

TABLE 7.

Results obtained in Special Direction-finding Test made at Orford with s.s. "Malines" on a Return Journey to Antwerp, 12–15 November, 1923.

Date	Time	Position of ship	From Orford				Remarks
			Distance	True bearing	Observed bearing	Error	
Outward Journey.			miles	degs.	degs.	degs.	
12/11/23	2220	Parkeston Quay	16·5	230·5	230·3*	— 0·2	Reliable D.F. readings; angles of swing less than 5°
12/11/23	2311	Cork L.V.‡	12·5	211·0	211·0	0·0	
12/11/23	2345	Sunk L.V.	16·0	171·8†	173·0	+ 1·2	
13/11/23	0003	Longsand L.V.	21·5	160·8	160·3	— 0·5	
13/11/23	0039	Galloper L.V.	30·5	145·3	146·3	+ 1·0	Flat min. angle of swing 20°
13/11/23	0209	N. Hinder L.V.	58·0	127·5	124·3	— 3·2	Reliable reading; angle of swing 3°
13/11/23	0319	Wandelaar L.V.	81·0	126·5	126·3	— 0·2	Unreliable; angle of swing 20°
13/11/23	0339	Wielingen Buoy	87·0	123·9	124·3	+ 0·4	Reliable; angles of swing 6° to 15°
13/11/23	0426	Flushing	101·0	117·3	117·5	+ 0·2	
Inward Journey.							
14/11/23	2315	Flushing	101·0	117·3	117·5	+ 0·2	Reliable; angle of swing 7°
15/11/23	0010	Wielingen Buoy	87·0	123·3	123·7	+ 0·4	Unreliable readings; angles of swing 25° to 40°
15/11/23	0039	Wandelaar L.V.	81·0	126·3	125·0	— 1·3	
15/11/23	0145	N. Hinder L.V.	58·0	129·9	132·5	+ 2·6	
15/11/23	0310	Galloper L.V.	30·5	145·3	145·5	+ 0·2	
15/11/23	0348	Longsand L.V.	21·5	160·8	160·0	— 0·8	Reliable readings; angles of swing less than 5°
15/11/23	0403	Sunk L.V.	16·0	171·4†	172·7	+ 1·3	
15/11/23	0434	Cork L.V.	12·5	211·0	210·7	— 0·3	
15/11/23	0455	Guard Buoy	15·0	228·8	228·0*	— 0·8	
15/11/23	0512	Parkeston Quay	16·5	230·5	231·0*	+ 0·5	

* Wireless bearings corrected by + 3° to compensate for direction-finding station error.
† Charted bearing corrected by + 2° to compensate for constant error experienced at these positions.
‡ L. V. = Light vessel.

Shipwash Buoy and light vessel, to compensate for the systematic error brought to notice at these positions.

The results given in Table 6 show that, assuming that the corrections made as above are justifiable, the maximum error of the wireless bearings throughout the test is 1·1°, all the remainder being correct to within 1°. It is also notable that, although in the case of the longest ranges employed the readings were marked "unreliable" on account of the flatness of the signal minima and consequent large angles of swing which were necessary to determine the bearings, the resulting errors are all less than 1°.

The test made on the journey to Antwerp was under very similar conditions. A strong wind prevailed at the direction-finding station for the sector 220°–240°, and also to the charted bearing taken on the Sunk light vessel. It would appear from the table that this correction, applied for the latter case, is scarcely sufficient, since the resulting errors are two of the five which exceed 1°. The only errors greater than 2° were obtained at the N. Hinder light ship, but as this was passed at a distance of 3 miles the estimate of the ship's position may not have been sufficiently accurate. The reading on the outward journey is notable since the direction-finding bearing was particularly sharp, the minimum being located with a swing of only 1·5° from its mid-position. In this test also, five readings were experienced as flat minima and were marked unreliable,

but the resulting errors are again small, three of the five being less than 1°.

A summary of the combined results obtained in these two tests is given in Table 8, which shows the high percentage accuracy of the wireless bearings obtained. It is to be observed that throughout these tests the usual phenomena of "wandering bearings" and "no detectable minimum" were experienced at Orford on of the order of 83 to 98 miles, the evidence supplied in Table 4 is sufficient to show that such direction-finding is practically useless for any navigational purpose at nights, when most serious errors are of very frequent occurrence. In some cases the observing operator is able to judge whether the bearing is a good one or not, but this judgment does not appear to be sufficiently reliable to be used as a working rule. The experience

TABLE 8.

Summary of Results obtained at Orford in the Two Special Tests with Ships' Transmissions, October and November, 1923.

Error in bearing	Reliable observations		Unreliable observations		All observations	
	Number	Per cent	Number	Per cent	Number	Per cent
Up to 1°	24	85·7	8	80·0	32	84·2
Up to 2°	27	95·4	9	90·0	36	94·7
Up to 3°	27	95·4	10	100·0	37	97·4
Up to 4°	28	100·0	—	—	38	100·0

the transmissions from Teddington, so that the wireless direction-finding conditions on these nights cannot be described as being in any way unusual.

6. CONCLUSIONS.

The accuracy to which wireless direction-finding can be carried out has both a practical and scientific interest. On the practical side those concerned with the application of direction-finding to marine navigation are anxious to know the most serious errors that are likely to be met with under various conditions and to know also what precautions are necessary to avoid these errors or reduce them to the minimum. On the other hand there are those who, while not being directly interested in the practical side of direction-finding, look to the results of its investigation for the shedding of light upon the more general problem of the propagation of electromagnetic waves over the earth's surface. It is thought that the results of the experiments here described will afford some tangible information of interest to both parties.

The general deductions to be drawn from this investigation may here be given as a conclusion to the present paper. With radio direction-finding apparatus of the type now obtainable for commercial use at a land station, the limiting accuracy of observed bearings which is obtainable by highly skilled operators under the most favourable conditions is of the order of 1°. To attain such an accuracy careful attention must be given to various details of the apparatus, and the installation must be calibrated somewhat elaborately for any local deviations. When operating over long periods of time the above accuracy is only maintained throughout both day and night for short ranges of the order of 10–16 miles. At greater distances up to about 200 miles the limit of error increases to about 2° and this can be maintained for daylight working only. When the transmission is entirely over land for distances of the author and other experimenters has shown that these variations and night effects are encountered at ranges down to about 30 miles over land.

When, however, the transmission is entirely over sea, so as to be well clear of any land effects, the accuracy of observed bearings is maintained within the limit of 2° for night as well as for day working at distances approaching 60 miles; and even up to 100 miles over 90 per cent of bearings are correct within 2°, the limiting error under ordinary working conditions being about 4°. Such an accuracy is probably good enough for most navigational purposes. The effect of an error of even this magnitude can be very much reduced by taking several observations at intervals of, say, 5 or 10 minutes. The above distances probably indicate the extreme ranges for accurate working for, as previously noted in the paper, many of the observed readings showed distinct signs of the approach of night errors as commonly experienced in transmission over land. Also, the results given in Table 5 for transmission from a land station entirely over sea show the errors which may be incurred at distances in excess of 80 miles.

For the successful application of direction-finding to the navigation of ships it is first necessary to obtain a good site for the direction-finding station, as free as possible from errors due to local disturbances. This latter source of error is not treated in the present paper, but it is well known that such objects as trees, overhead wires, cliffs and mountains, etc., produce serious disturbances in the neighbourhood of a direction-finding station. With satisfactory conditions prevailing at the receiver, reliability of observed bearings is secured at distances of 60 to 100 miles when the path of transmission is over sea and in a direction well away from land and coast lines.

Should the path of transmission include more than about 16 miles of land, variable errors are likely to be encountered at night in addition to the ordinary coastal

error at all times. From the results given above it will be evident that the taking of check bearings on a fixed station transmitting over land affords no indication whatever as to the reliability of bearings observed on a ship at sea at the same periods. What is usually required by the navigator of a ship at sea, however, is not a line bearing but a position fix; but, assuming the same error in wireless bearings to be obtainable by two or more direction-finding stations, the accuracy to which such a position fix can be given by simultaneous observations is a matter of mere geometry. The extension of the present investigation to cover the operation of two or more direction-finding stations *on the coast* was not considered sufficiently useful to justify the expense involved.

The result of the investigation which is of more scientific interest is that the minimum range of transmission for the occurrence of the well-known phenomena of night effects on closed loop direction-finders is about three times as great over sea as that over land. The exact ratio is possibly dependent upon the relative conductivities of the sea and land, and the resulting attenuation accompanying the propagation of the electromagnetic waves. While some of the existing theories may account for these effects in a qualitative manner, experimental evidence is lacking in other directions, and a purely theoretical discussion is considered to be outside the scope of the present paper.

This investigation was carried out for the Radio Research Board under the direction of the Committee on Directional Wireless, the members of this Committee being as follows:—Mr. F. E. Smith, C.B.E., F.R.S. (*Chairman*); Mr. F. W. Davey; Mr. C. E. Horton, B.A.; Capt. C. T. Hughes, M.C., R.E.; Dr. J. Robinson, M.B.E.; Dr. C. G. Simpson, F.R.S.; Dr. R. L. Smith-Rose; and Mr. O. F. Brown, M.A., B.Sc. (*Secretary*).

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DISCUSSION ON

"DIRECTIONS FOR THE STUDY OF VARNISH-PAPER AND VARNISH-FABRIC BOARDS AND TUBES."*

Dr. H. M. Barlow (*communicated*): I am surprised to observe that the British Electrical and Allied Industries Research Association have repeated an error which is really inherent to the method employed for measuring the internal resistance of these dielectrics. Some time ago Mr. H. L. Curtis of the Bureau of Standards put forward (*Bulletin of the Bureau of Standards*, 1914, vol. 11, p. 359) various tests for determining the properties of solid dielectrics, the internal resistance being measured by placing the sample between two mercury electrodes. The present Report of the Association has adopted practically the same procedure. In my paper on "An Investigation of the Friction between Sliding Surfaces" which immediately precedes this Report (see page 133), I believe I have established beyond doubt that the contact resistance between mercury and these so-called semi-conductors is always large compared with the true internal body resistance of the material. Once the electricity has been transferred from the electrode to the semi-conductor, it passes relatively easily through its mass, and it is the interface which mainly provides the insulating property. In view of the fact that my original thesis was in the hands of the Electrical Research Association in May 1923, it appears that the fallacy involved in the method advocated has not yet been realized, and that the actual conditions are not properly understood. The matter seems to me to be very important, both scientifically and commercially. I venture to suggest that there are few, if any, switchboard makers who realize that the insulation between the positive and negative busbars is almost entirely provided by the contacts between the fixing bolts and the slate or marble employed. To sum up, perhaps I may repeat what I said in my recent paper: "such materials as slate, red fibre, paxolin and celluloid can only be classed as dielectrics in virtue of their high contact resistance, and . . . the true body conductivity of these semi-conductors cannot be measured with mercury electrodes."

Mr. E. B. Wedmore (*in reply*): Dr. Barlow, in the report to which he refers, demonstrates that with certain materials, for instance slate and lithographic stone, the surface-resistance phenomena are so large as to screen such internal resistance as the material

* Report of the British Electrical and Allied Industries Research Association (see page 160).

may have, when any attempt is made to investigate this resistance by the usual methods. This is a valuable contribution to knowledge on the subject and opens a very wide question, but it must not be hastily assumed that this same result will be found to be characteristic of poor insulators in general, or that the methods advocated by the Bureau of Standards and by the Electrical Research Association serve no useful purpose. At the present time these methods are the best known for the examination of the resistivity of large and important classes of insulating materials. It is as yet too soon to define in what classes of material the surface phenomena are so important as to require the use of some other method. The validity of the methods advocated has been proved over and over again with large numbers of materials, some of good and some of inferior insulating properties, and the Electrical Research Association have made it their business to advocate the general use of the best known method. Dr. Barlow has indicated that he found similar phenomena in dealing with varnish-paper board, red fibre and celluloid, but hitherto he has furnished no data on the subject. Until further data are available we do not know to what extent the surface properties influence the results in dealing with these materials. The work of the Electrical Research Association has shown that on the market there are examples of these materials very defective in insulating properties, and we have, in fact, had examples of varnish-paper board which were practically conductors at ordinary temperatures. Nevertheless, it has been shown experimentally that by the methods advocated we can detect differences in quality between different samples of the various materials in question and it has yet to be shown that the Association are in error in this matter. This can be done only by showing that a material which is not suitable for its purpose may be approved for use in the industry under the methods advocated. This is not a scientific, but a practical point. Revolutions in practice may arise out of scientific discoveries, but much spade work is required to bring them about. Further research will no doubt result in the development of a method of testing the surface properties and isolating them, but no one is yet in a position to offer a test for this purpose suitable for general use. Developments on these lines may introduce some revolutionary changes, but if one takes the extreme case of slate, I cannot see that any change in practice is in prospect. The switchboard manufacturer knows from long experience that the electric strength of slate is adequate, but that the insulation resistance is low and an uncertain quantity. In the relatively few cases where high insulation resistance is required he obtains it by bushing the holes. Dr. Barlow's observations do not point to any change of practice in this connection, and if any change were indicated it is likely that the research would have to be repeated employing materials as used in the industry, i.e. not wetted prior to test. Every research undertaken by the Electrical Research Association on insulating materials has produced new evidence of the urgent necessity of making a scientific attack on the whole subject of dielectrics, as the observed phenomena of resistivity and electric strength are full of anomalies. The importance of the subject is shown by the fact that the insulation repair bill of the electrical industry is of the order of one million pounds per annum. To deal with this problem at all adequately will require much larger funds than have hitherto been available, but there is no doubt that the provision of such funds would be a very good investment by the electrical industry.

SOME FACTORS AFFECTING THE WORKING COSTS OF SMALL ELECTRIC GENERATING SETS.*

By E. G. KENNARD, Associate Member.

(*Paper first received 28th December, 1923, and in final form 24th March, 1924.*)

SUMMARY.

The paper is intended to show how the working costs per unit of electricity are influenced by various factors, viz. type of engine, nature and magnitude of load, price and calorific value of fuels.

Internal-combustion engines only have been considered, as these are practically the only types in use for small modern plants.

TABLE OF CONTENTS.

(1) INTRODUCTION.

Although many papers and technical articles dealing with the economical generation of electricity on a large scale have been published, the question of costs for small lighting and power plants has not received the amount of attention it deserves, considering the many thousands of these sets there are in use. The author has consequently endeavoured to give comparisons of costs for generating current, using various types of small internal-combustion engines under various working conditions.

Special attention has been given to the several causes which influence the thermal efficiency of internal-combustion engines, and, although this subject is proper to the field of mechanical engineering, the data given should be of use to electrical engineers in designing new plants, and also in the improvement of working costs for existing ones.

(2) SUMMARY OF TESTS ON SMALL INTERNAL-COMBUSTION ENGINES.

In Table 1 a summary is given of published tests on small internal-combustion engines adapted to work with various fuels. These have been selected from various sources, and should therefore be representative of modern practice.

The brake thermal efficiency is calculated from the total number of therms in the fuel consumed per hour at full load by the engine, and from the brake horsepower at full load, from which, calculating from Joule's mechanical equivalent of heat, the value 0·0254 therm per b.h.p.-hour is obtained.

(3) COMPARISON OF THERMAL EFFICIENCIES OF VARIOUS TYPES OF ENGINE.

In Fig. 1 the brake thermal efficiencies for the various types of engine have been plotted from the values given in Table 1. It will be observed that efficiencies vary considerably for various types and rated outputs, the lowest value being 14 per cent for a high-speed petrol engine, and the highest value 32 per cent

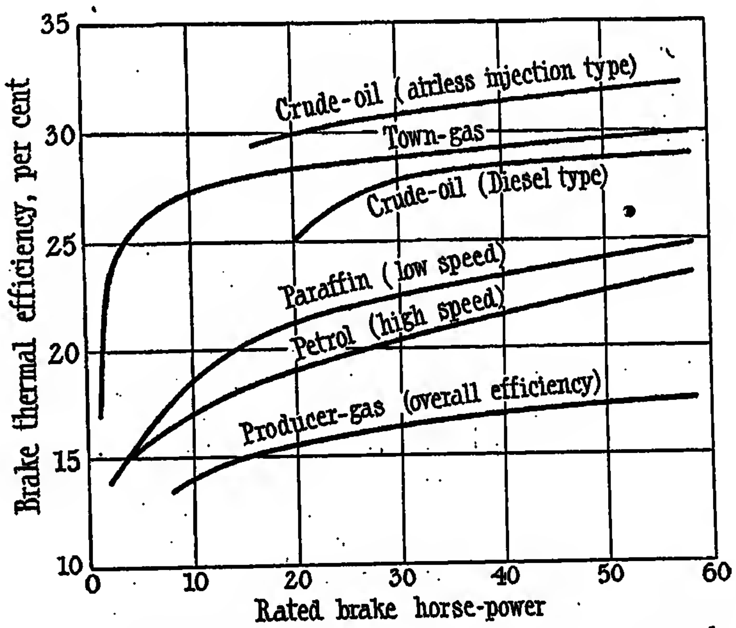

FIG. 1.—Full-load brake thermal efficiency of internal-combustion engines.

for the latest pattern of crude-oil engine (airless injection type). These differ from the Diesel pattern in the respect that pure air only is compressed up to ignition temperature, and the oil charge is not introduced until the exact moment for the explosion. It will be noticed that these engines are not obtainable in ratings of less than 15 b.h.p. The town-gas engine comes next in order of efficiency, a good curve being obtained which drops rapidly below 5 b.h.p. The Diesel type of crude-oil engine takes the next place, and is seen to compare favourably with the town-gas engine. Here again these are not manufactured in small sizes much below 20 b.h.p. The next curve in order of efficiency is for

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

the ordinary oil engine which burns paraffin or kerosene as fuel. These engines are made in two general patterns :—

(*a*) Using an external vaporizer.
(*b*) Vaporization obtained by spraying into a heated chamber extension of the cylinder.

Fig. 1 shows the efficiency curves for class (*b*), which are of higher efficiency than class (*a*), these being of the same order as for petrol engines. The next curve gives the efficiency for high-speed petrol engines. It may be noted that at low rated horse-powers this curve gives approximately the same values as are obtained for the paraffin engine, but the increase in efficiency is not so marked when larger outputs are reached. The last curve is for engines driven by producer gas. In general, the actual thermal efficiencies are only slightly lower than those of the gas engine, but the values shown in the figure include the producer losses.

Some causes of variation in thermal efficiency.—The main factors affecting engine efficiency are :—

Calorific value of explosive mixture.
Degree of compression employed.
Temperature of explosive charge.
Temperature of cooling water.
Mechanical efficiency of engine.
Degree of combustion.
Dimensions of engine cylinder.

Some properties of the various fuels used for the engines considered have been obtained, and are given in Table 2.

TABLE 1.

Tests by Various Authorities on Internal-combustion Engines.

Type of engine	Rated: Power	Rated: Speed	Heat consumption, therms per hour: No load	¼ load	½ load	¾ load	Full load	Brake thermal efficiency	Mechanical efficiency	Authority for test figures	Remarks
	b.h.p.	r.p.m.						%	%		
Town gas	2·5	300	0·07	—	0·22	—	0·27	23·5	—	Test by Author	
	5·2	260	—	—	—	—	—	26·7	84	Tests for Inst.C.E. (1905)	
	21	200	—	—	—	—	1·88	28·3	85		
	28	190	0·45	0·87	1·4	—	2·38	29·8	—	*Practical Engineer*, 1920	
	53	166	—	—	—	—	4·52	29·8	86	Inst.C.E, 1905	
Producer gas	8	230	—	—	0·93	—	1·5	14	—	Royal Automobile Society's tests (1906)	Anthracite fuel
	20	190	—	—	2·25	—	3·3	15·5	—		
	40	—	—	—	—	—	6·0	17	—	—	Coke fuel
	45	200	—	—	—	—	7·6	15	—	"Industrial India," vol. 1, no. 7.	Wood refuse
	55	160	—	—	—	—	8·1	17·2	—	National Engine Co.	Coke fuel
Petrol (4-cycle)	2·5	1 270	—	—	—	—	0·396	16·0	80	Prof. Callendar	
	19	985	—	—	—	—	2·72	17·8	85	Messrs. White & Poppe's tests, from Clerk & Burls's book	Average of tests on 192 engines
	33·5	985	—	—	—	—	4·05	21	85		
	42·5	985	—	—	—	—	4·9	22	86		
	55	985	—	—	—	—	5·63	24·8	85		
	20	1 000	—	—	—	—	2·64	19·3	—	Test due to Wimperis	
Paraffin	5·3	220	0·2	—	0·66	—	0·90	15	—	Fielding & Platt	Described in "The Gas, Petrol and Oil Engine" (vol. 2), by Messrs. Clerk & Burls
	10	260	0·51	—	0·75	—	1·25	20·3	—	Clerk & Burls	
	18	220	0·74	—	1·14	—	2·25	21	—		
	32	230	—	—	—	—	3·60	22·6	—		
Crude oil	19·6	172	—	—	—	—	—	25·2	75	Schroter at Augeburg	Diesel pattern
	35	180	1·38	1·53	2·1	2·7	3·4	28·9	75·0	H. A. Clark for Harrogate Corporation	
	80	160	1·44	2·74	4·0	5·3	6·6	30·4	78·3	M. Ade Clark at Ghent	
	15	300	—	—	—	—	1·3	29·3	—	Captain Sankey for the Ruston Engine Co.	"Airless Injection" type
	38	250	0·675	1·17	1·59	2·21	2·9	33·3	—		

It is evident that in no sense is the thermal efficiency of an engine proportional to the calorific value of the fuel used.

Item 5.—The values for the gaseous fuels were obtained from a table given in Clerk's book, "The Gas, Petrol and Oil Engine" (vol. 1), and the values for the hydrocarbon fuels were calculated.

Item 6.—It will be noted that although there is such a wide variation in the calorific value per cubic foot of gaseous vapours, there is relatively little difference between various explosive mixtures of gas and air, and

it will be seen that a fuel having a high calorific value requires a large amount of air, and vice versa, so that too much importance need not be attached to calorific values of fuel in connection with thermal efficiency. It is found in practice that the proportion of fuel and air in the mixture required to obtain maximum power does not coincide with the correct mixture for maximum thermal efficiency. The figures given below for gas engines are due to Prof. Hopkinson. His tests on a 32 h.p. engine using town gas show :—

	Weak mixture	Strong mixture
Calorific value (B.Th.U. per cub. ft.)	48	63
Indicated h.p.	39·3	45
Indicated thermal efficiency ..	37 %	33 %

With weaker mixtures than that shown above it was found difficult to fire the charge regularly.

tent igniting at the lower temperatures. It is necessary to allow a large margin of safety, partly because pre-ignition is also caused by particles of hot carbon inside the cylinder.

Correct temperature for the cooling water.—If the cylinder is kept too cool the exploded gases lose heat too rapidly, causing a reduction in the mean effective pressure. If kept too hot the volumetric efficiency is affected, resulting in a reduced charge of mixture, but the pumping losses are also lower. The effect of cooling-water temperature on the pumping loss has been measured by Prof. Hopkinson on a 40 h.p. gas engine at 180 r.p.m., and he found that with normal lubrication the mechanical loss was reduced from 6 h.p. to 4¾ h.p. by increasing the temperature of the jacket water from 70° F. to 180° F. This point has also been investigated by Mr. Morse in the form of tests on a 14 h.p. 4-cylinder Daimler motor.* The higher relative heat consumption

TABLE 2.

Properties of Fuels.

	Town gas	Coke producer gas	Crude oil	Petrol vapour	Paraffin vapour
Calorific value (net), B.Th.U. per lb. ..	—	—	18 000	18 500	19 500
Present price per lb.	—	0·214d.	0·485d.	3·0d.	1·64d.
Price per therm	7·0d.*	2·14d.	2·7d.	16·3d.	8·5d.
Calorific value, B.Th.U. per cub. ft. of gas .	500	130	—	4 650	6 450
Cub. ft. of air per cub. ft. of gas to effect combustion	5·0	1·1	—	49	63
Resultant calorific value of mixture (theoretical), B.Th.U.	83	62	—	93	102
Compression ratios commonly employed ..	5½/1	6½/1	14/1	4½/1	4/1
Approximate explosion temperature of mixture	850° F.	910° F.	910° F.	900° F.	900° F.

* Price in London at power rate.

Prof. Watson also arrives at the same conclusion for petrol engines † :—

	Weak mixture	Strong mixture
Ratio of air to petrol	17/1	12/1
Calorific value	83	116
Indicated h.p.	16·2	19·9
Indicated thermal efficiency ..	27·5 %	22·2 %

It will be noticed that the calorific value of the mixture is much higher for the petrol engine. This explains why less power is obtained when a petrol engine is worked from town gas.

Item 7.—Compression values usually employed. Generally speaking, thermal efficiencies are increased with higher compression. The limit for working compression values depend partly on the temperature at which pre-ignition is liable to take place.

Item 8.—This shows the probable ignition temperatures for the various fuels, those with a large hydrogen con-

† *Proceedings of the Institution of Automobile Engineers*, 1908–9, vol. 3, p. 387.

at no load in his tests shown below is due to greater mechanical losses.

	Full load	Half load	Light load
Speed, r.p.m.	720	720	720
Brake horse-power ..	14·5	7·4	0·6
Friction, horse-power ..	0·74	0·74	0·74
Pumping loss, horse-power	0·36	0·58	1·45
Indicated horse-power ..	15·6	8·72	2·79

This increase in pumping loss at light load, was shown to be due partly to throttling and partly to the lower temperature of cooling water, the contraction of the cylinder causing higher friction loss.

These tests confirm the general opinion amongst gas engine experts that it is more efficient to keep the cylinders at about 150° F. for small engines.

* *Proceedings of the Institution of Automobile Engineers*, 1908–9, vol. 3, p. 274.

We may sum up the various causes which affect engine efficiency as follows :—

(*a*) It is found that within certain limits the thermal efficiency decreases with an increase in the calorific value of the mixture (probably due to imperfect combustion), and indicated power increases with the calorific value of the mixture.

(*b*) Up to a certain point higher compression gives higher efficiency, but the gain due to higher compression is sometimes nullified by increased heat loss due to the greater ratio of surface to volume in the compression chamber. The best degree of compression depends also on the fuel employed.

(*c*) An increase in temperature reduces the weight of the entering charge, affecting the thermal efficiency. In some types of engines (such as paraffin or petrol) initial heat is, however, required to vaporize the fuel.

(*d*) An increase in cylinder dimensions gives a higher thermal efficiency; a high-speed engine with two or more cylinders is, therefore, less efficient than an engine of similar power having one cylinder (see Callendar's formula given below).

(*e*) Raising the cooling-water temperature tends to increase the efficiency, as shown by the test previously referred to.

(*f*) Mechanical efficiencies also vary considerably in various types of engines.

Thus the variation in thermal efficiency for the engines shown in Fig. 1 is accounted for. In addition, with petrol or paraffin engines a very careful adjustment of mixture is required to effect complete combustion, otherwise unburnt gases find their way into the exhaust. Tests on 12 motor-car engines, carried out by the Royal Automobile Club in 1907, showed 2 per cent and upwards of carbon monoxide (an explosive gas) present in the exhaust gases.

(4) Full-load Running Costs of Generating Sets.

It will be noticed from Table 1 that there are very few test-figures of engines below 5 h.p. In order to fix some values for thermal efficiency of low-power engines the portion of the curve for town-gas engines below 5 h.p. has been calculated from Prof. Callendar's formula :

$$\text{Thermal efficiency} = 0\cdot75\,E\,(1 - 1/D)$$

where E = "air standard" efficiency at desired compression,
D = cylinder diameter, in inches.

Makers of generating sets have found it advisable to allow a certain margin of excess engine power over dynamo output; for example, one finds a 4 kW dynamo coupled to an 8 h.p. engine. Assuming the dynamo to be of 82 per cent efficiency this gives a loss of 950 watts at full load. Allowing 5 per cent for belt or transmission loss this gives a further loss of 250 watts, making a total power of 5 200 watts, or an equivalent of 7 h.p., thus leaving a margin of 1 h.p. On this basis the running costs in pence per unit have been worked out, for different types of engines and sets, at the prices of fuel shown in Table 2, and the results are plotted in Fig. 2. It will be observed that producer-gas sets and crude-oil engines are not obtainable in the smaller output, nor are paraffin engines of the non-vaporizer type below 2 h.p. Five per cent has been added to the fuel costs to allow for lubricating oil and water, except for producer-gas sets where 10 per cent has been added, as a considerable amount of water is used for the scrubbers and is run to waste. No allowance has been made for wages for running the plant. Small plants do not require very much attention during normal running periods, and are often attended to by the owners. The costs of maintenance repairs is included later under capital charges. It will be seen that town-gas sets are much more economical for outputs up to 4 kW than are either petrol or paraffin sets, the running costs for petrol and town-gas sets being in the ratio of 3 : 1, with town gas at 7d. per therm.

The difference between producer-gas and crude oil for larger sets is not very marked, but the

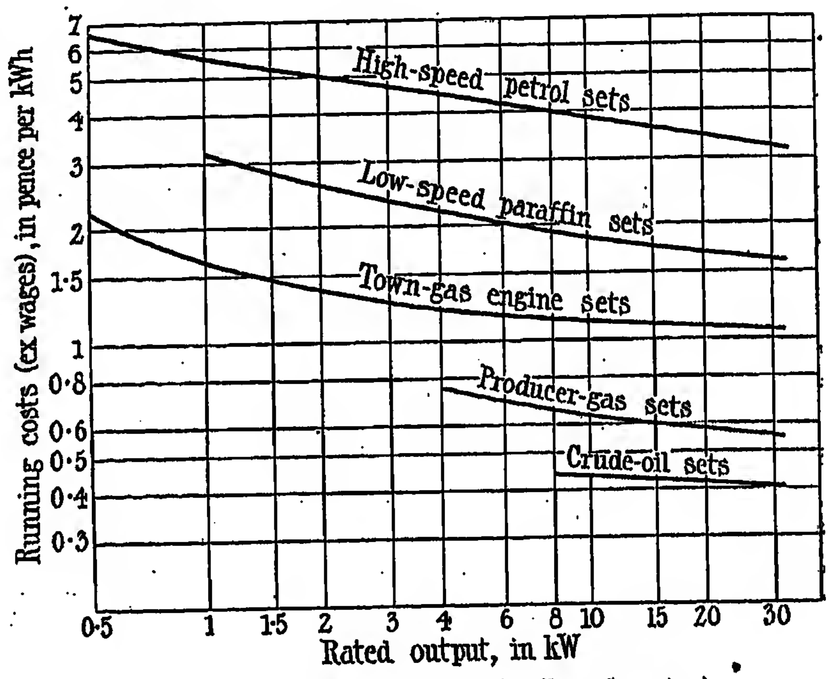

Fig. 2.—Running costs (fuel, oil and water).

ratio of costs as between petrol and crude-oil sets is approximately 10 : 1; the petrol set labours under two great disadvantages, namely, low thermal efficiency and high price of fuel.

When it is realized that all these internal-combustion engines are, broadly speaking, of the same type, the difference in the running costs is remarkable.

(5) Effect of Load Factor on Working Costs.

The above figures are not, however, a reliable guide to the choice of a generating set unless they are taken in conjunction with considerations of load factor and capital outlay. Some representative costs for engines, dynamos and necessary switchgear have been obtained for the various types of sets. It may be stated that wide variations in price are found on comparing several makers' lists; the prices selected, however, represent plant of the best quality. Owing to lack of space the author has not included the various items, but, as a convenient basis for subsequent working, the total charges for each type of set have been reduced to pence per unit at 10 per cent load factor. Ten per

cent per annum on the total outlay has been allotted to cover capital and maintenance charges, and the load factor is based on the rated output of the set working continuously throughout the year.

For plants working on lighting load only, the load factor ranges from 7 per cent to 12·5 per cent according to the requirements of the consumer. Taking 10 per cent as an average figure, the following standing charges in pence per unit generated are obtained :—

Rated output = ½ kW		2 kW	8 kW	32 kW
	per unit	per unit	per unit	per unit
Petrol plant ..	3·15d.	1·35d.	0·75d.	0·50d.
Paraffin plant ..	—	1·65d.	1·0d.	0·66d.
Town-gas plant	3·5d.	1·57d.	0·93d.	0·63d.
Producer plant .	—	—	1·78d.	0·85d.
Crude-oil plant .	—	—	1·3d.	0·8d.

These figures indicate the importance of taking capital charges into account, especially in the case of small sets working at low load factor.

Only in exceptional circumstances are lighting plants required to furnish current to light all the lamps continuously connected to the circuit, and in the majority of cases the load varies considerably. If a storage battery be used, the load may be equalized during lighting hours by charging the battery in parallel with the lamps. The effect on the total working cost of using a storage battery has been investigated, but there are many variable factors to be considered and it is not possible to include the material in the present paper. The results point to the conclusion that if current is required only during the normal period of lighting each evening, the addition of a storage battery to the plant will not enable working costs to be reduced very much, as the increased capital charges for the battery and the considerable losses which occur in charging tend to offset the gain due to working the engine at its most efficient load. If, therefore, sets are used for lighting without storage batteries, before the working costs can be estimated it is necessary to know not only the load factor but also the average load on the set. If the normal lighting period throughout the year be taken to extend from dusk until 11 p.m. each evening, the total number of lighting hours per year will be approximately 1 620. Calculating on a basis of 10 per cent load factor for lighting sets the average load is

$$\frac{\text{kW} \times 8\,670 \text{ hours}}{10 \times 1\,620} = \text{approx. } 0{\cdot}5 \text{ or half load}$$

To get an accurate idea of the normal running cost for a lighting plant, it is necessary to know how the fuel consumption varies with the load.

Fuel consumption of engines at various loads.—Some figures from various published tests are shown in Table 1. If the fuel consumption at different loads be plotted, it is interesting to note that in most cases the points will lie in practically a straight line between one-quarter load and full load, but at no load there is a tendency for the curve to bend upwards. The no-load consumption is considerable, and if it is expressed as a percentage of the full-load heat consumption it ranges from 33 per cent for a 1 h.p. engine down to 22 per cent for a 60 h.p. engine. Taking proportional values for these no-load figures at intermediate engine sizes, and given the full-load brake thermal efficiency of an engine, an approximate value can be determined for the heat consumption at intermediate loads by plotting no-load and full-load values and joining the two points by a straight line.

In the case of electric generating sets the engine is never actually working on no load, as it has to provide for the constant losses of a fully-excited dynamo, and also the belt or transmission losses. This may cause the no-load consumption to be considerable, especially in the smaller sizes where the dynamo efficiency is comparatively low. Having made allowance for these extra losses some figures are given below for the number of therms consumed per hour by the engine at the loads indicated, using town gas as fuel.

kW output	No load	Half load	Full load
½	0·055	0·095	0·135
1	0·090	0·150	0·210
2	0·14	0·250	0·370
4	0·24	0·450	0·670
8	0·40	0·850	1·26
16	0·70	1·60	2·40
32	1·3	3·0	4·50

A study of these figures enables the following comparisons to be made :—

(1) The heat consumed at no load varies from 40 per cent of the full-load value in the ½ kW size, to 29 per cent in the 32 kW size.

(2) The heat consumption of any set at no load is approximately equal to the half-load consumption of a smaller set of one-half the rated output.

(3) The same amount of gas required to operate a set at full load will give approximately half the amount of electrical energy if a set of twice the rated output is used.

To get economical results, therefore, it is important not to have a larger set than is necessary and also to avoid running on very light loads for long periods.

Fig. 3 shows the (total capital running) costs at 10 per cent load factor for various types of sets. These values are based on the running costs for each type operating at one-half the rated load, and therefore represent with fair accuracy the average price of current per unit. The addition of a storage battery would not influence these costs to any great extent, because the extra capital costs and battery losses would be balanced by the improved economy due to the higher average load on the generating set.

Some interesting conclusions may be drawn from these results. In a country district where town gas is not available, a small lighting set of ½ kW capacity

supplies current at a total cost of 1s. per unit. Lower costs are obtained for petrol, with a 1 kW set at 10d. per unit, or 7d. per unit using a low-speed paraffin engine. Using engines driven by town gas, ½ kW to 1 kW output costs from 6d. to 4½d. per unit, a figure which compares favourably with the charges made by electric supply authorities.

The costs for sets worked by producer gas, at the

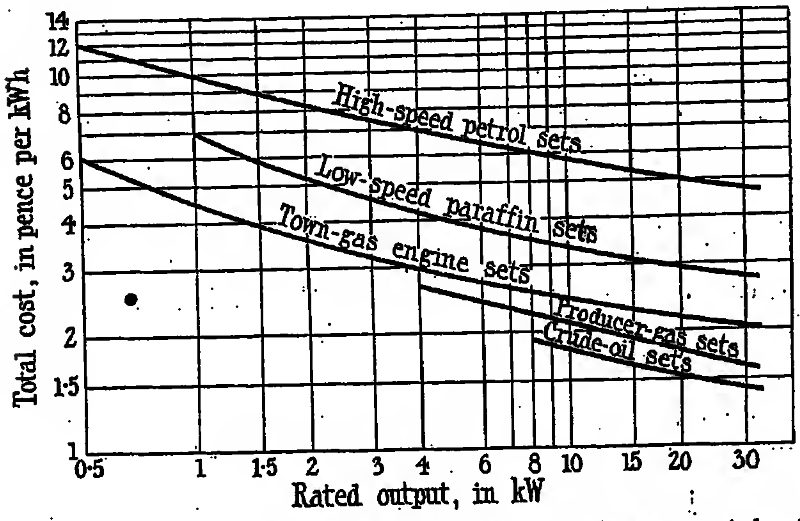

FIG. 3.—Total costs per kWh, based on 10 per cent load factor and an average load of one-half the rated output.

present price of coke and anthracite, show that very little is saved by using it instead of town gas, although in some cases it is profitable where wood sawdust or chips can be employed. Where the load is sufficiently great to require a plant of 8 kW and above, crude-oil sets can be used with advantage, the total costs per

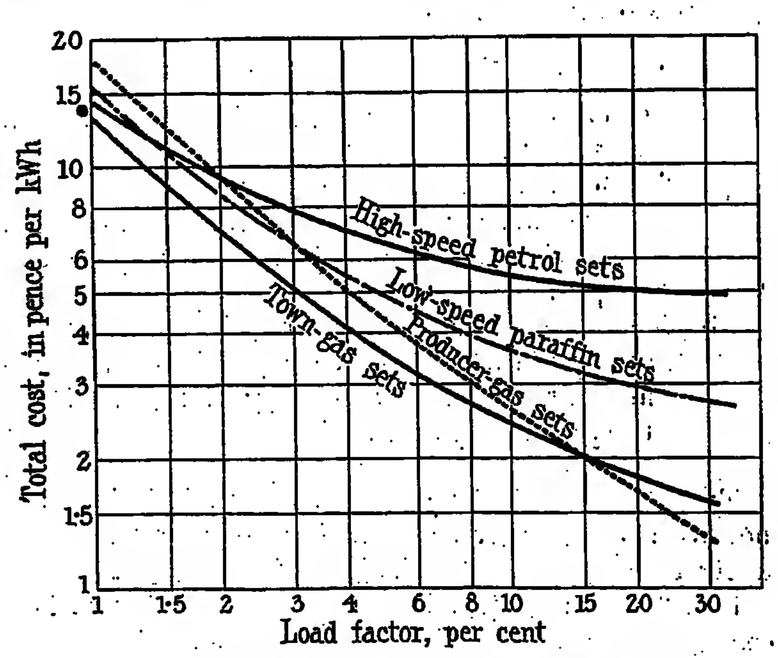

FIG. 4.—Total costs per kWh, using sets of 4 kW rated capacity at different load factors.

unit being less than 1·8d. All small generating sets used for lighting only have the same disadvantage of low load factor, resulting in a somewhat high capital charge per unit.

To show the influence of load factors on total working costs some curves have been plotted in Fig. 4 for sets of 4 kW rated output running on full load. It will be noticed that producer-gas sets are only more economical than town-gas sets (at 7d. per therm) above a load factor of 15 per cent, also that below 2 per cent load factor they are less economical than petrol sets. Lighting loads in this country for sets constantly in use would rarely have a load factor of less than 5 per cent, and below that value would indicate work of an intermittent character, such as is performed by portable sets, and here the petrol set is seen to its best advantage.

(6) THE INFLUENCE OF A DOMESTIC HEATING AND COOKING LOAD.

If the plant be utilized for cooking and domestic apparatus an improvement in load factor is possible, and in this connection reference may be made to some experiments of the Glasgow Corporation described *

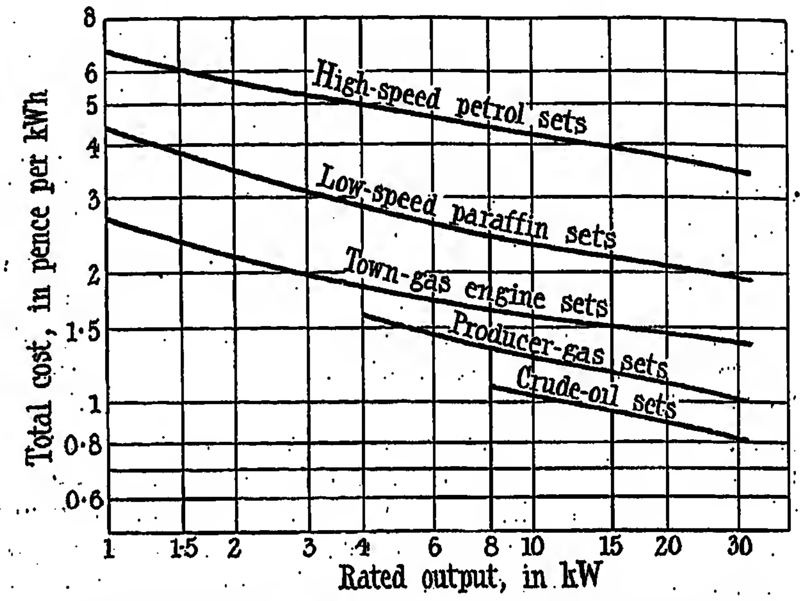

FIG. 5.—Total costs per kWh for plants used for lighting, heating and cooking, at a load factor of 20 per cent.

by Councillor Denny. Two small houses were fitted up as "all electric" houses, no coal, gas or form of heating other than electricity being used. The apparatus installed in each house consisted of:—

One 3 kW oven.
One ½ kW kettle.
One 1 kW immersion heater.
One 3 kW radiator.
One 1½ kW radiator.
One 1 kW radiator.
One ½ kW smoothing iron.

Total 10½ kW.

Allowing for ½ kW of lighting, this makes a total of 11 kW connected, or a probable maximum load of 6 kW. The actual number of units consumed per annum was 10 520 (average of two houses), and the load factor is therefore approximately 20 per cent. If these houses were individually supplied from a small plant instead of from the mains, it would be a simple matter to arrange for the plant to operate mostly at full load without the use of a large storage battery, as variations in load could be equalized by the thermal storage of hot water.

Fig. 5 shows costs for various types of generating

* *Electrical Review*, 1920, vol. 86, p. 675.

sets at 20 per cent load factor and working on full load. It will be seen that for a 6 kW plant the costs per unit are :—

	d.
Petrol engine	4·5
Paraffin engine	2·6
Town-gas engine..	1·70
Producer-gas engine	1·45

As the current for the Glasgow experiment was obtained at the low price of approximately 0·78d. per unit, it will be seen from the curves in Fig. 5 that only in the producer-gas or crude-oil sets of 20–30 kW would an "all electric" house supply be economical where the working cost per unit is between 0·8d. and 0·9d. If it is proposed to use a plant to furnish current for all domestic needs the number of units generated by the 6 kW plant would be allocated approximately as follows :—

	Units
Heating	8 000
Cooking	2 000
Lighting	500
Total	10 500 units

(7) The Utilization of Waste Heat from the Engine.

At the prices of current shown above for a 6 kW set it would not be economical to generate electricity for heating purposes, but a better plan than this would be to use as much as possible of the heat rejected by the engine. A study of tests made by some of the authorities referred to in Table 2, indicate that for a 12 h.p. engine the heat balance-sheet is approximately as follows :—

	Percentage of total heat supplied
Brake horse-power	28
Heat taken up by cooling water	28
Heat taken away by exhaust gases	32
Loss in engine bearings and pumping friction	5
Radiation loss from engine	7
Total heat	100

The heat from two of the sources of loss shown above is recoverable for domestic purposes, namely the hot water from the cooling jacket, and the heated exhaust gases, the latter of which will readily transfer the bulk of their heat to water in some form of calorimeter.

If the engine be located close to the house, then with suitably lagged pipes a quantity of hot water will be available for heating, washing and cleaning purposes, a small rotary pump being added if necessary to assist the circulation. As the 12 h.p. engine at approximately full load consumes 1·1 therms per hour, the total recoverable heat would be 0·66 therm. Allowing for one-third of this to be lost, 0·44 therm is available for heating purposes, as against 0·3 therm delivered as brake horse-power, or, after deducting dynamo and driving losses, the useful electrical energy is 0·22 therm. Thus for every kilowatt-hour of current generated, 2 kWh of heat which otherwise would be lost would be recoverable in the form of hot water. It would thus be possible to put down a plant to supply lighting, power, electrical heat for cooking and hot water for heating and domestic purposes, at quite a reasonable cost.

Out of a total of 10 500 units per annum, 2 500 are absorbed by the lamps and cooking apparatus, thus releasing the equivalent of 5 000 in hot water. Out of the remaining 3 000 units to make the required total of 8 000, it would only be necessary to generate 1 000 electrically. This would be conveniently used by electric radiators for "topping up" purposes. Calculating the working costs on this basis for a set designed to supply lighting, cooking and heating for the 10 500 units-per-annum house, the electrical load would be reduced from 6 kW to 2 kW. It would be necessary to include a storage battery for the lighting load, and it would be advisable to install one of sufficient capacity to carry the greater part of such load.

The approximate total costs for a set of 2 kW capacity using town gas at 7d. per therm and generating 3 500 units per annum, will be 2·2d. per unit. The equivalent cost per unit allowing for the use of engine waste heat will be (2·2d./3) + 15 per cent for extra battery costs = 0·8d. per unit, corresponding to the charge per unit made at Glasgow. Even when it is not desired to install a plant of sufficient size for purposes other than lighting, arrangements could be made to furnish a certain amount of hot water according to the output of the set.

In conclusion, the author desires to draw attention to the fact that the figures for working costs are based on prices of fuels obtaining at the time the paper was written, and these are subject to some variation from time to time, especially in the case of oil fuels. It is probable, however, that the general conclusions will not be very much affected unless some very large changes in price take place.

THE ATKINSON-TYPE REPULSION MACHINE AS A MOTOR AND GENERATOR.*

By F. J. Teago, M.Sc., Member.

(*Paper first received* 27*th November*, 1923, *and in final form*, 24*th January*, 1924.)

Summary.

The following notes are the result of experiments made by research students, under the direction of the author, on a 25-period single-phase Atkinson-type repulsion motor in the Laboratories of Applied Electricity, Liverpool University. The work involved in preparing Part I was carried out by O. J. Crompton, C. G. Ramsay and E. W. Young. That entailed in the preparation of Part II was performed by T. W. Dann.

In the first place a vector diagram for the motor, in line with the standard diagram for a single-phase series commutator motor, has been developed. It is then shown how, by means of brush shifting, the motor may be made to operate as a generator.

It is obvious that regeneration by means of brush shifting has limitations in its practical application. To obviate these limitations regeneration with a fixed brush-position and a reversed field coil was investigated. This was found to be a function of the speed and could not be varied independently. Finally, by injecting an E.M.F. into the armature short-circuit, with fixed brush-position and reversed field, it has been found possible to control the amount of power regenerated at any given speed.

Synopsis of Contents.

Introduction.

In the treatment of the graphical representation of the action of the simple repulsion motor, it is usual to split the single magnetic field of the motor into two components, as follows:—

(*a*) One component at right angles in space to the line along which the armature is split by the brushes. This component provides the magnetic field with which the armature current reacts to produce rotation.

(*b*) One component coincident in space with the line along which the armature is split by the brushes. This component induces the current in the armature which reacts with the magnetic field as previously mentioned.

The Atkinson type of repulsion motor is provided with two stator windings, and the brush gear can be so set that these two windings produce the two hypothetical components of a single-field motor. Under these conditions the brushes are said to be in the neutral position.

In the following notes the vector diagram of such a motor is evolved from experimental data, and, since the two hypothetical components of the single field actually exist in this case, the behaviour of the motor is capable of being expressed in terms of these two components and the results can be checked by actual measurements.

It must be clearly borne in mind that, in these notes, it is assumed that the two components of the magnetic field are permanently in space quadrature and that forces tending to distort this condition are negligibly small.

Notation.

The stator winding producing the flux in which the armature rotates is termed the field winding, whilst that which induces the torque-producing current in the armature is termed the transformer winding.

In the armature, the coils short-circuited by reason of the fact that the brushes bridge two neighbouring commutator segments are referred to as the auxiliary short-circuit, whilst the coils short-circuited by connecting the positive brush terminal to the negative terminal are termed the main short-circuit.

The following symbols are used throughout:—

V_S = total supply voltage.
V_F = supply voltage on field coil at speed.
V_C = supply voltage on transformer coil at speed.
$V_{F'}$ = supply voltage on field coil at standstill.
$V_{C'}$ = supply voltage on transformer coil at standstill.
Φ_F = flux due to field coil at speed.
Φ_C = flux due to transformer coil at speed.
$\Phi_{F'}$ = flux due to field coil at standstill.
$\Phi_{C'}$ = flux due to transformer coil at standstill.
V_T = main transformer E.M.F. in armature due to transformer flux, and is in quadrature with $\Phi_{C'}$.
V_R = main rotational E.M.F. in armature due to field flux, and is in time phase with Φ_F.
V_A = main resultant E.M.F. in armature.
V_t = auxiliary transformer E.M.F. in armature due to field flux, and is in quadrature with $\Phi_{F'}$.
V_r = auxiliary rotational E.M.F. in armature due to transformer flux, and is in time phase opposition to Φ_C.
e = auxiliary commutation E.M.F. in armature.
v = resultant of V_r and e.
I_s = supply current to field and transformer coils.
I_A = current in main armature short-circuit.
I_a = current in auxiliary armature short-circuit.

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Part I.

(By O. J. Crompton, C. G. Ramsay and E. W. Young.)

The Atkinson-type Repulsion Motor.

In the Atkinson-type repulsion motor, assume that the field flux and rotational directions are as shown

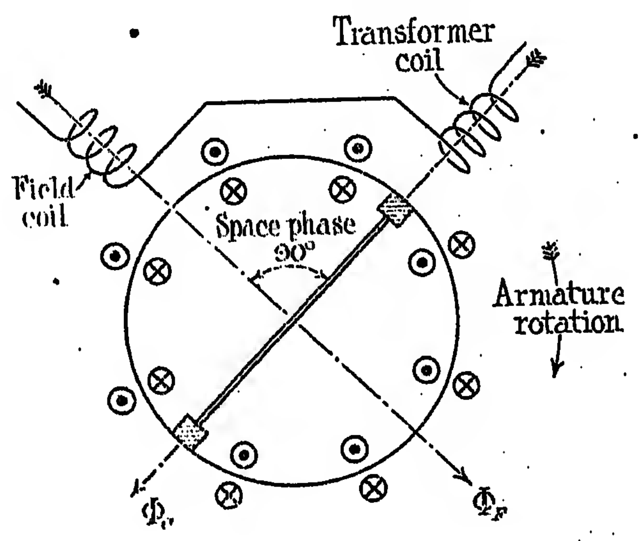

Fig. 1.

in Fig. 1. Then the induced armature current must be as shown by the outer conductors, and to produce this current the direction of the transformer flux must be as shown. The back E.M.F. generated by the rotation of the armature in the field flux is shown by the inner conductors.

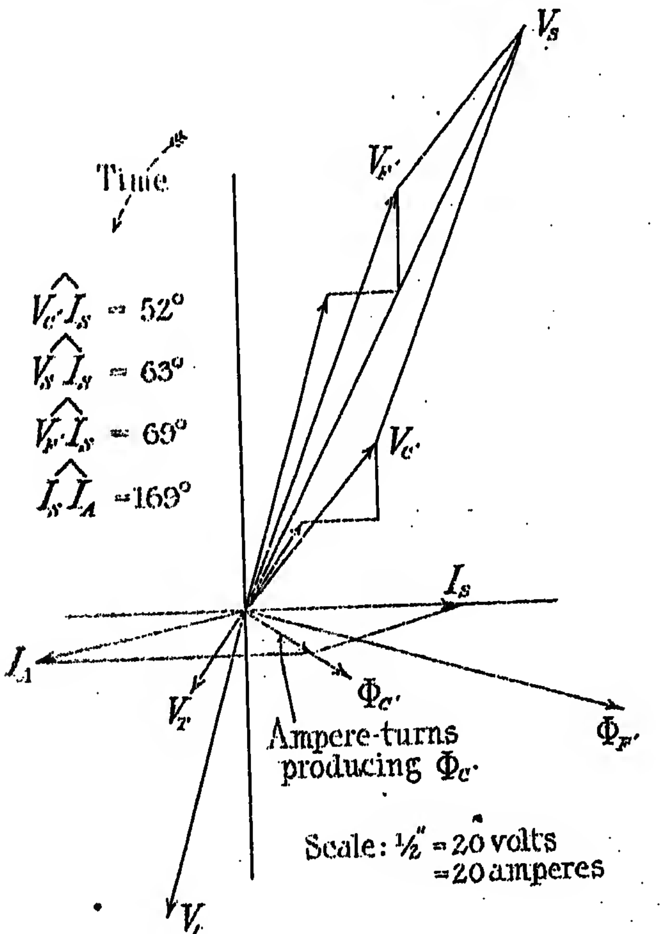

Fig. 2.—Vector diagram for motor at standstill.

Fig. 2 shows the vector diagram for the motor at standstill. The voltages V_S, $V_{F'}$ and $V_{C'}$ are meter readings, as are also the currents I_s and I_A, and these vectors are drawn to scale. The vector I_s has been chosen as a reference and drawn in a horizontal position, and the angles between this vector and the others are as indicated and were measured on an oscillograph of the falling-plate type.*

Fig. 3 shows the vector diagram for the motor at a speed of 450 r.p.m. V_S, V_F, V_C, I_s and I_A are meter readings and are drawn to scale. Their angles with respect to I_s were measured on the oscillograph.

Comparing Figs. 2 and 3 it is noticed that the time phases of the fluxes with respect to I_s change considerably as the speed changes. This point is dealt with later.

It is also seen that, although the angle between $V_{F'}$ and $V_{C'}$ remains unaltered and relatively small, the angle between V_F and V_C is considerable and is a function of the speed.

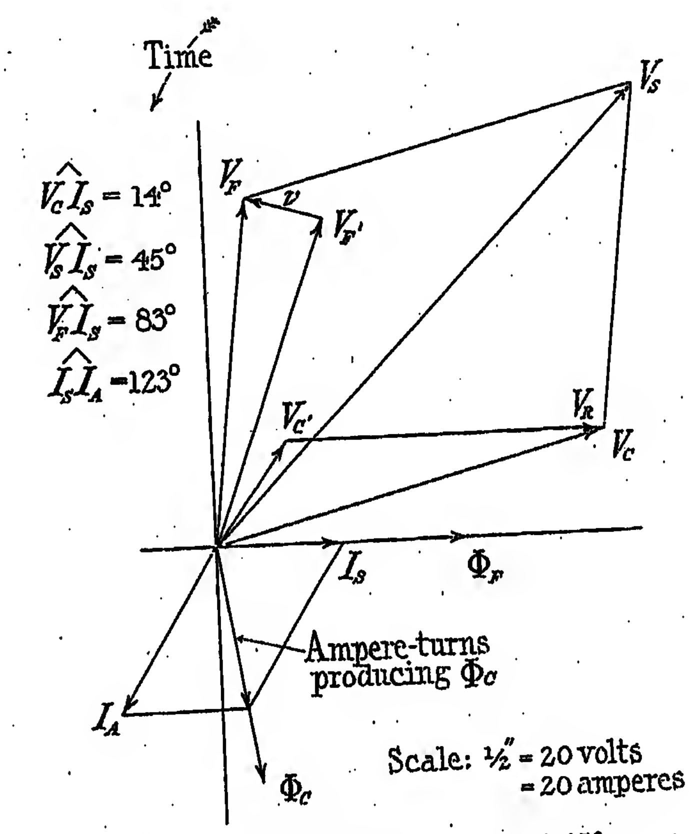

Fig. 3.—Vector diagram for motor at 450 r.p.m.

The voltage $V_{C'}$ at standstill.—As shown in Fig. 2, $V_{C'}$ is the vector sum of the component to balance V_T which is in quadrature with $\Phi_{C'}$, the component in phase with I_s to balance the resistance drop in the transformer coil, and the component in quadrature with the I_s to balance the leakage-inductance drop in the transformer coil.

Under these conditions, $V_{C'}$ cannot be very large, because V_T is small. This is so because V_T is produced by $\Phi_{C'}$ which is due to the resultant $I_s I_A$ ampere-turns. As can be seen from Fig. 2, these resultant ampere-turns are small, and therefore $\Phi_{C'}$ is small. The voltage $V_{C'}$ will, of course, be proportional to the magnitudes of the standstill values of I_s and I_A.

* The angle between I_s and $V_{F'}$, also that between I_s and $V_{C'}$, is practically independent of the value of I_s when the motor is at standstill in this case, but this may not be quite true in cases where there is saturation in the leakage flux paths, and the magnitudes of these angles must depend upon the design features of the motor under consideration. For convenience, although not strictly true, $\Phi_{C'}$ is shown in time phase with the ampere-turns producing it, and since $V_{F'}$ leads relatively to $V_{C'}$ therefore Φ_F is in advance of $\Phi_{C'}$, but no attempt has been made accurately to determine the angle between these two fluxes.

The voltage V_C at speed.—The transformer coil voltage at any speed is assumed to be made up of :—

(*a*) The voltage required to offset the E.M.F. V_R generated in the armature at that speed by the field flux due to the current I_s.*

(*b*) The standstill value of $V_{C'}$ corresponding to the current I_s.

To determine the component (*a*), the field coil only is excited with a current equal to I_s, the main short-circuit being open and the armature driven at the required speed. If the transformer coil were excited, then a transformer E.M.F. would be induced in the armature.

Experimentally it is found that the above method is correct (see Fig. 3), and, since Φ_F must be parallel to V_R, this method also provides a means of ascertaining the time-phase-angle between I_s and Φ_F at any speed.

That V_R is a component part of V_C can be easily seen when it is remembered that Fig. 1 shows that V_R is a back E.M.F. and would reduce the E.M.F. induced by the transformer flux unless V_C had a component to offset V_R.

The voltage $V_{F'}$ at standstill.—Owing to the relatively small number of ampere-turns in the auxiliary short-

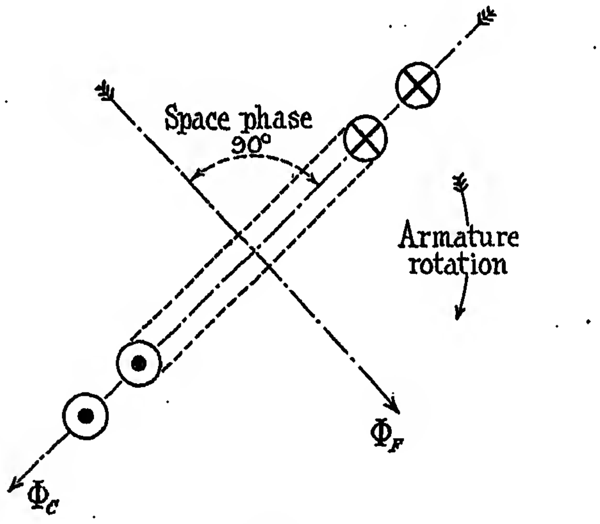

FIG. 4.

circuit compared with the ampere-turns due to the current I_s in the field coil, the flux $\Phi_{F'}$ is more nearly in time phase with I_s than is the flux $\Phi_{C'}$ (see Fig. 2). Also, as can be seen, the resultant ampere-turns producing $\Phi_{F'}$ are larger than those producing $\Phi_{C'}$. This tends to make V_t larger than V_T. $V_{F'}$ is made up of the component to balance V_t, together with the components to balance the resistance and leakage-inductance drops in the field coil, in the same manner as has been described in connection with $V_{C'}$.

Owing to the fact that $\Phi_{F'}$ is larger than $\Phi_{C'}$ and is more nearly in time phase with I_s, the voltage $V_{F'}$ is larger than $V_{C'}$ and is in advance of it, as shown in Fig. 2. These conclusions are confirmed by the experimental data obtained.

The voltage V_F at speed.—Fig. 4 shows the space position of the auxiliary short-circuit relative to the space positions of Φ_F and Φ_C. As in the case of any ordinary drum-wound armature, the auxiliary short-circuit is in space quadrature with the field flux, as shown.

The transformer E.M.F. induced by the field flux $\Phi_{F'}$ is shown by the outer conductors, and the current flowing would tend to rotate the armature backwards by reason of its interaction with the transformer flux Φ_C.

Actually, however, the auxiliary short-circuit is driven in the direction shown, since the torque due to the main short-circuit predominates. Thus the rotational E.M.F. due to the transformer flux Φ_C is as shown by the inner conductors. In Fig. 4, then, V_t and V_r act in the same direction, whereas in Fig. 1 V_T and V_R act in opposition, and this leads to the conclusion that, since in Fig. 3 V_R is in time phase with Φ_F, then V_r in Fig. 5 must be in time phase opposition to Φ_C, where

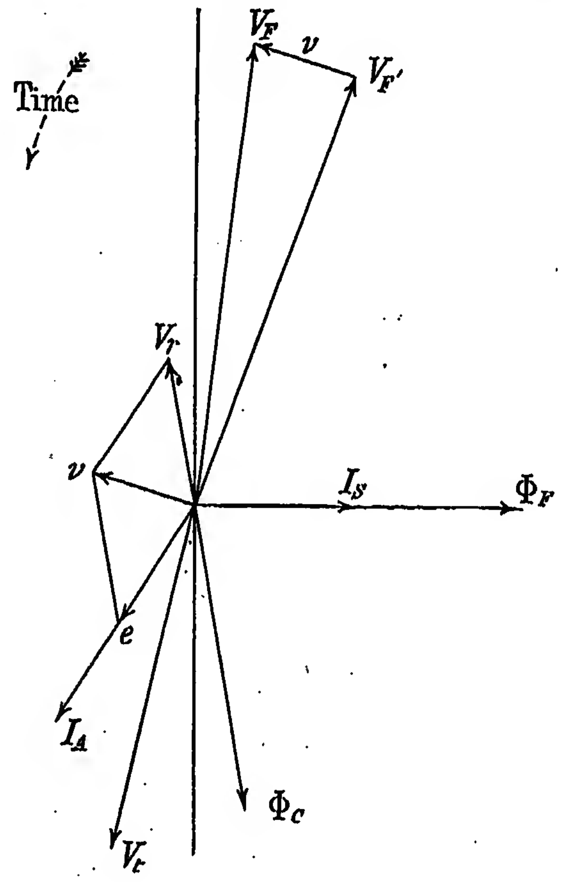

FIG. 5.

it is shown together with the commutation E.M.F. which is proportional to the current I_A.

Fig. 5 also shows v as the resultant of V_r and e, and that, in a manner similar to the case of the transformer coil voltage, the speed voltage on the field coil is made up of :—

(*a*) the voltage required to offset v, and

(*b*) the standstill value of $V_{F'}$ corresponding to the current I_s.

THE GENERAL CHARACTERISTICS OF THE REPULSION MOTOR.

The characteristics of the repulsion motor are much the same as those of the series motor; that is, the supply current and torque are maxima at the lowest speed. The armature current, however, does not vary with the supply current as it does in the series motor, but remains sensibly constant at all speeds (see Figs. 2

* I_s is assumed to be the supply current to the motor when operating against some particular torque at the particular speed under consideration.

and 3) unless the brushes are displaced from the neutral position. This can be explained as follows :—

Fig. 6 shows the experimentally determined magnitudes and time phases of I_s and I_A at 450 r.p.m. Fig. 6 also shows that the armature current I_A can be split up into two components which are practically in quadrature with each other.

One of the components $(-I_s)$ can be assumed to be induced in the armature by the transformer flux $\Phi_{C'}$ and to be equal to, except for the magnetizing current, the supply current I_s. This component, then, behaves precisely like the armature current of a plain series motor, and the torque is produced by the interaction of the current, $-I_s$, and the field flux Φ_{F}. The component I_R may be assumed to be produced by V_R, the E.M.F. due to the armature speed in the flux Φ_F. This current I_R is in quadrature with V_R except for a power component equal to its copper loss in the armature; it does not, therefore, appear in the supply current and, under these conditions, V_R is a pure back E.M.F., exactly as it is in the plain series motor and it increases in magnitude as the speed of the motor increases.

Thus as the speed of the motor increases, the $-I_s$ component of I_A decreases as it does in the case of the

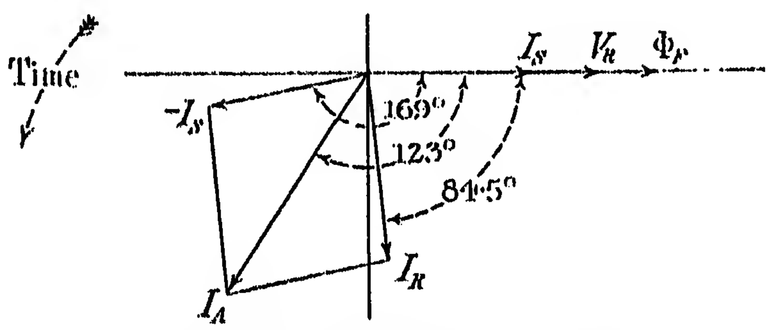

FIG. 6.—Experimentally determined magnitudes of I_s and I_A at 450 r.p.m.

plain series motor, whilst the I_R component increases because V_R increases, so that the resultant armature current I_A tends to remain of constant magnitude and move more into time phase with I_s.

If, however, it is preferred to regard I_A as the torque-producing current, then although this current is sensibly constant at all speeds, it must be remembered that the higher the speed the more nearly time quadrature exists between I_A and Φ_F. This, in conjunction with the decrease in Φ_F with increasing speed, explains why the motor has a series characteristic, and also why the motor fails to race, as the series motor does on no load.* Since the behaviour of the repulsion motor is very much like that of the series motor, it is desirable that its vector diagram should be drawn in line with the standard diagram for the series motor, and this has been done.

One great advantage of these diagrams (Figs. 2, 3 and 5) is that the time phase differences between I_s and $V_{C'}$ and $V_{F'}$ remain sensibly constant for all values of I_s, and this means that the standstill positions of $\Phi_{C'}$ and $\Phi_{F'}$ are fixed for all values of the supply current. Thus it becomes an easy matter to build up $V_{C'}$, the magnitude of which is given by the standstill value of the voltage on the transformer coil when taking a current equal to the particular current taken by the motor when operating at the speed for which the diagram is to be drawn. If the magnitude and time phase of V_C, the speed value of the transformer coil voltage, corresponding to this current is also determined, then the rotational E.M.F. V_R becomes a determinate quantity and, since the speed position of Φ_F must be parallel to V_R, it becomes an easy matter to find the amount of time phase-movement in the field flux which that particular speed has caused.

The construction for the field portion of the vector diagram is carried out in a similar manner.

The power factor of the repulsion motor increases as the speed increases, and this can be readily seen from Figs. 2, 3 and 5 when it is remembered that an increase of speed causes the voltage on the transformer coil to increase and approach I_s, whilst the field coil voltage is affected only slightly. Thus V_s approaches I_s as the speed increases, and it improves the power factor.

Part II.

(By T. W. DANN.)

THE EFFECT OF BRUSH MOVEMENT WHEN THE MOTOR SPEED IS UNRESTRICTED.

In the vector diagrams developed in Part I the brushes are assumed to be in the neutral position. If, with a repulsion motor of the Atkinson type, the brushes are rocked from the neutral, then the speed changes as shown in Fig. 7.

As might be expected from Part I, an increase in speed is accompanied by an increase in the power factor of the motor, whilst a decrease in speed lowers the power factor.

THE EFFECT OF BRUSH MOVEMENT ON THE VECTOR DIAGRAM WHEN THE MOTOR SPEED IS ARTIFICIALLY MAINTAINED CONSTANT.

The effect of brush movement upon the vector diagram for a constant speed of 450 r.p.m. can be seen by referring to Fig. 8.

Here it is noticed that a backward brush movement of two commutator segments increases the power factor from 0·707 to 0·934, whilst an equal forward movement decreases the power factor to 0·358.

Taking V_S as the fixed reference vector, these three diagrams show that I_s changes greatly both in time phase and in magnitude, that although I_A changes in magnitude its time phase-change is only slight,* and that the other vectors change very little either in time phase or magnitude.

With regard to the voltages V_F and V_C it might be pointed out that at standstill, for the same amount of brush rocking, they vary considerably, so that it is the speed which has the effect of maintaining them approximately constant.

It has been shown in Part I that variations in V_F

* Although the repulsion motor is said to have a series characteristic it must not be forgotten that the speed at no load is limited and that the speed of a plain series motor is unlimited, so that the repulsion motor cannot have a pure series characteristic.

* The power factor of the main short-circuit is practically independent of the brush position.

and V_C are accompanied by corresponding variations in the fluxes Φ_F and Φ_C, so that in the case under consideration it might be assumed that these fluxes remain of constant magnitude and time phase with respect to V_S, and if the fluxes are constant then the ampere-turns producing them are also constant. With respect to the transformer-coil voltage V_C, a statement such as follows is generally true :—

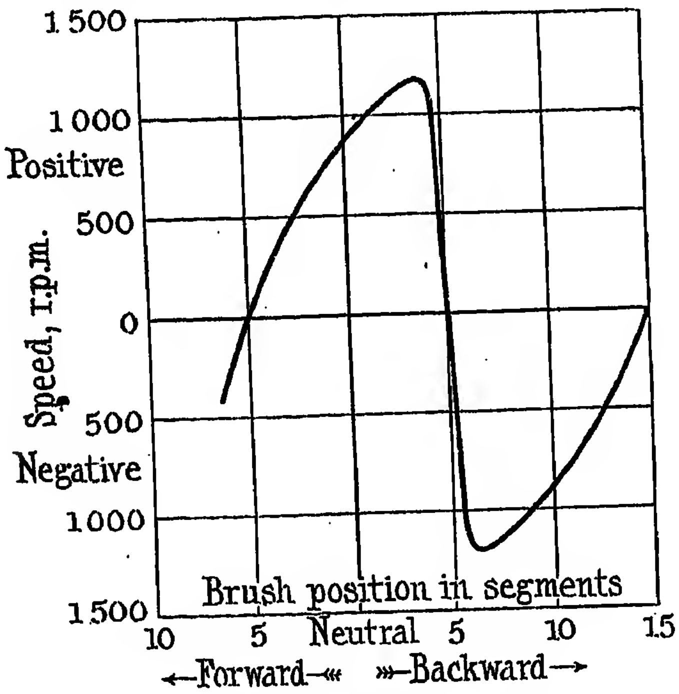

FIG. 7.

If the brushes are moved from the neutral position and the speed is artificially maintained constant, then the changes in I_s and I_A are such that their resultant is constant in time phase and magnitude.

Fig. 8, on the assumption that the variation in the magnitude of the angle between V_S and I_A is negligible, shows the general truth of the statement. In a similar manner it can be shown that the ampere-turns producing Φ_F remain approximately constant.

The power factor of the motor cannot be improved indefinitely by brush rocking, nor can it be decreased below a certain value, because the magnitude and time phase of the resultant of I_s and I_A are definitely fixed, and this fixes the limiting positions of I_s.

The variation in the magnitudes of the currents may be explained, in general, as follows :—

As the brushes are rocked backward the speed of the motor tends to rise and the increased resisting torque, necessary to maintain the speed normal, demands an increased supply current. Similarly, when the brushes are rocked forward a decreased supply current is taken.

REGENERATING BY BRUSH SHIFTING AT CONSTANT SPEED.

Fig. 8 shows that as the brushes are rocked forward the supply current diminishes, and its time lag is increased relatively to the supply voltage.

In the neighbourhood of five segments (45 electrical degrees) forward, this time lag becomes 90 degrees and the motor stops. If the brushes are moved further forward, then, owing to the reversal of the current in the armature, the motor reverses.

If, however, the speed of the motor is maintained artificially constant, and in the original direction, then as the brushes are moved forward the current passes through a minimum value, but continues steadily to increase its time lag relatively to V_s, getting gradually into phase opposition.

As soon as the current lags behind the voltage by more than 90 degrees the power in the circuit reverses and the machine begins to act as a generator.

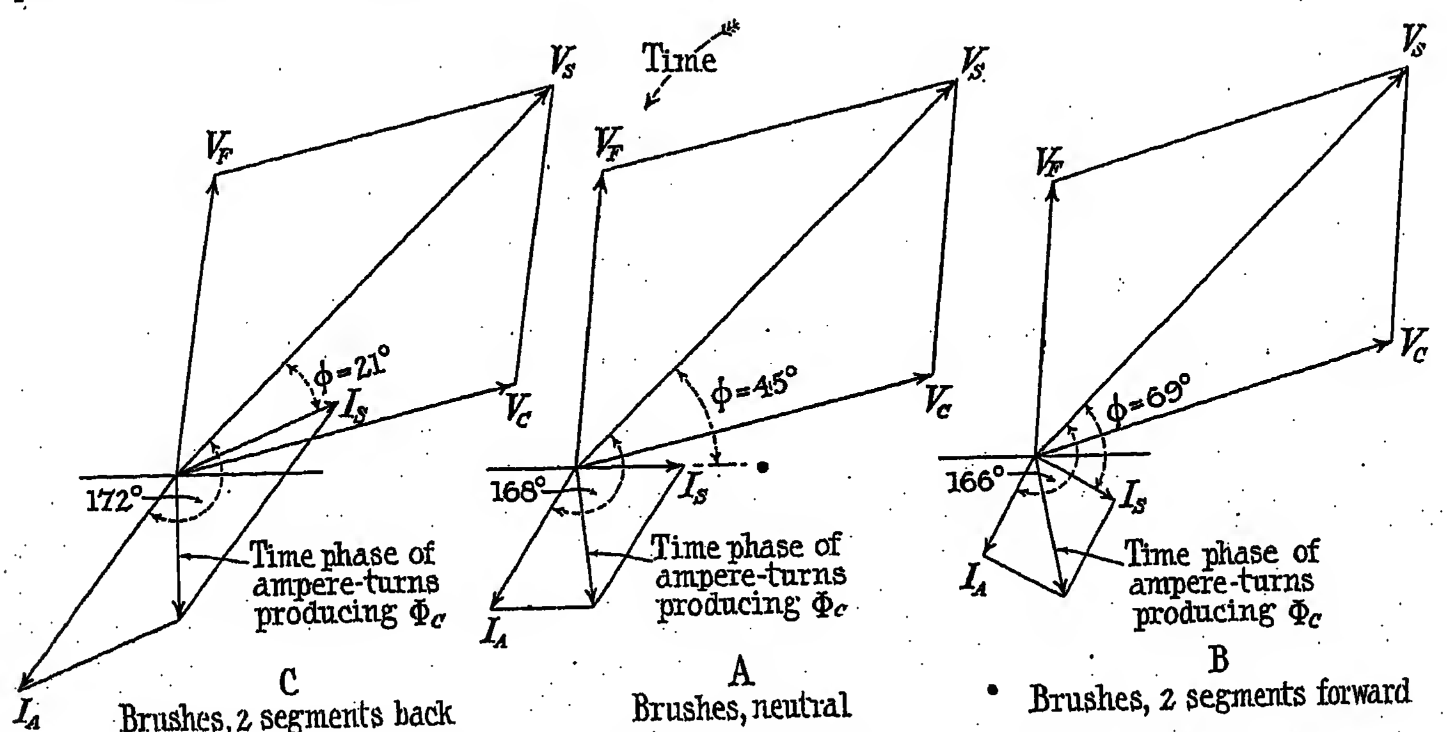

FIG. 8.—Effect of brush movement upon the vector diagram for a constant speed of 450 r.p.m.

Fig. 9 shows how, for a constant speed of 710 r.p.m., the current, power factor and power vary as the brushes are rocked forward, and Fig. 10 is typical of the vector diagram for the machine when operating as a generator under these conditions.

In a manner similar to that described in the case of the motor, the resultant ampere-turns producing Φ_C have to remain constant in time phase and magnitude, so that there is a limit to the power factor of regeneration, and regeneration at a leading power factor would only be possible where the inherent motor operation is at a leading power factor.

Regeneration is also possible when the brushes are rocked backward, but before the generating zone is reached in this direction very heavy current values, between three and four times the full-load current of the motor, are passed through.

In direct contrast to this, when the brushes are rocked forward a minimum value of the current is passed through and a rapidly rising power factor is obtained, so that regeneration from this side is gradual and progressive.

The rapid rise of the power factor over this part of the curve is very marked, and on taking a small overload

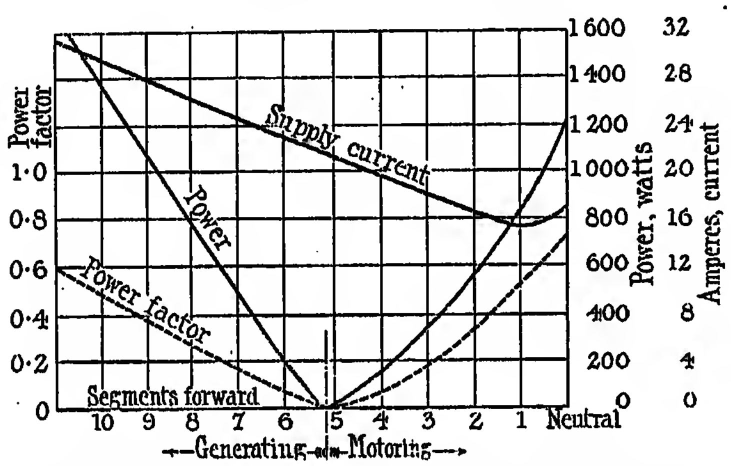

Fig. 9.—Variation of current, power factor and power with change in position of brushes at a constant speed of 710 r.p.m.

current it is possible to regenerate the full output of the machine.

Fig. 9 shows that at 710 r.p.m. with the brushes 7·5 segments forward the machine generates 50 per cent of its output as a motor, yet at 9·5 segments forward with approximately 14 per cent more current it regenerates the full motor output.

It is therefore possible to obtain regenerated power at any speed by merely regulating the position of the brushes on the commutator.

Regeneration with Fixed Brushes and a Reversed Field Coil.

To avoid moving the brushes in order to cause the machine to act as a generator, it was decided to reverse the field-coil connections, since a reversed field coil corresponds to a brush movement of 90 electrical degrees.

When the field coil is reversed the machine normally reverses its direction of rotation. If, however, the rotation is kept in the original direction by means of an auxiliary motor, then there is a fairly low critical speed, above which the machine acts as a generator (c.f. induction generator) having a power factor which increases as the speed increases.

The vector diagram for the machine acting as a generator under these conditions at 450 r.p.m. is shown by Fig. 10, and the critical speed is the speed at which the time phase-angle between V_S and I_s becomes 90 degrees.

At 225 r.p.m. the angle ϕ (Fig. 10) has a cosine of 0·074, which rises to 0·41 at 450 r.p.m.

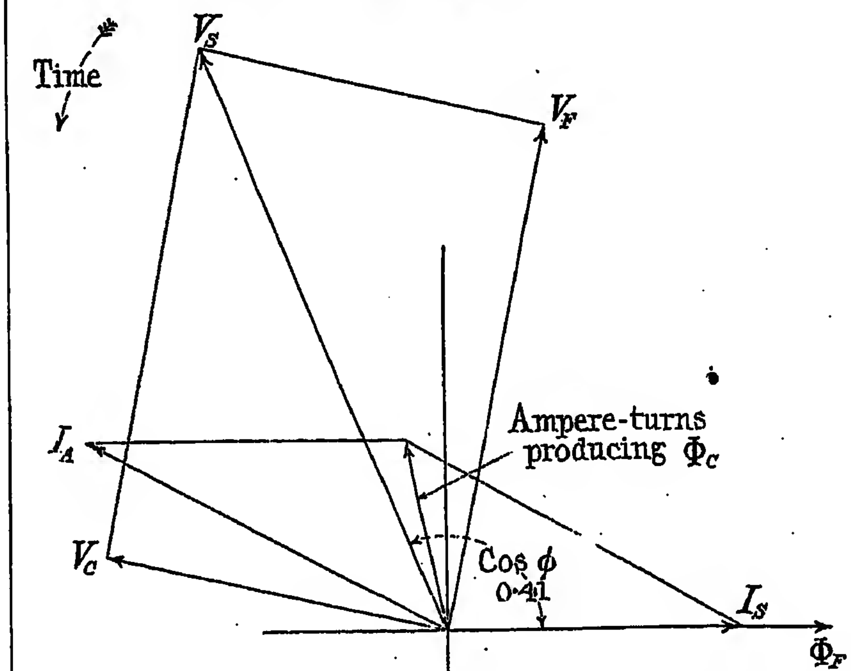

Fig. 10.—Vector diagram for machine acting as generator at 450 r.p.m.

In connection with Fig. 10, it should be remembered:

That the reversal of the field coil causes a reversal of the rotational E.M.F. V_R.

That a motor E.M.F. is less than its applied P.D., whereas a generator E.M.F. is greater than its terminal voltage.

That in the section on brush movement it has been

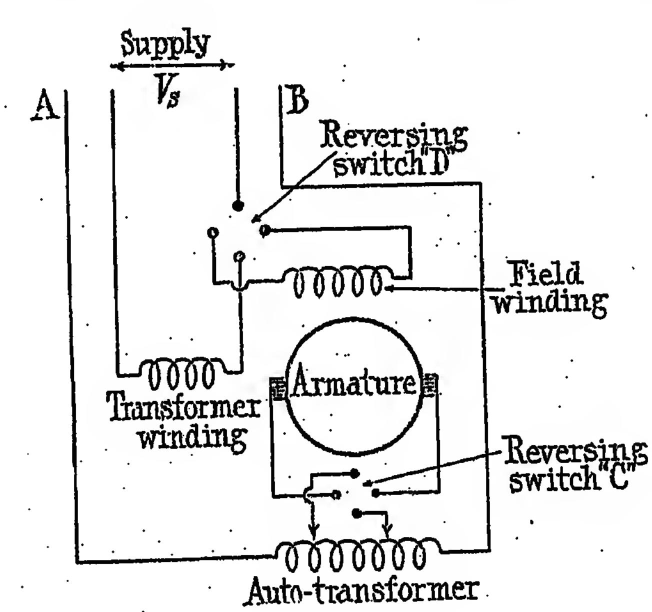

Fig. 11.

assumed that the machine changes from a motor to a generator when the supply current lags behind the supply voltage by more than 90 degrees. Fig. 10, therefore, represents generator conditions, because I_s lags behind V_S by more than 90 degrees.

That the field and transformer-coil voltages bear the same relative time phase-relationship to their fluxes as they do in Fig. 3.

It should be noticed that, at a speed of 450 r.p.m., Φ_C in Fig. 10 is in advance of Φ_F, whereas in Fig. 3 it lags behind Φ_F, and that this change is due to the time phase-change of I_A which is caused by the reversal of V_R.

The standstill conditions for Fig. 10 are the same as for Fig. 2.

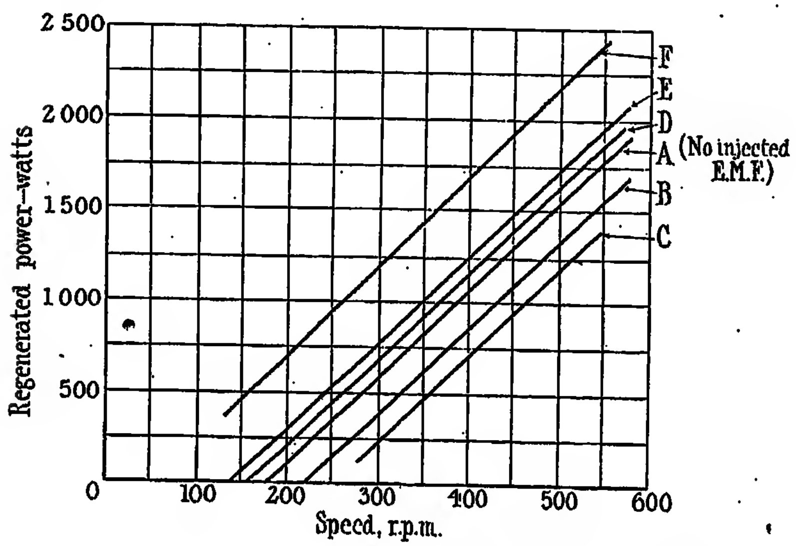

FIG. 12.—Variation in regenerated power with speed.

Regeneration with the field coil reversed is a very simple and convenient matter, but the amount of power regenerated at any one speed is a fixed quantity.

REGENERATION WITH THE INJECTION OF AN E.M.F. INTO THE MAIN SHORT-CIRCUIT.

When the repulsion motor with its field reversed is acting as a generator there is no control over the amount of power which may be regenerated at any particular speed.

With the object of modifying these limiting conditions, the motor was connected up as in Fig. 11. The lines A and B were connected across a supply and an E.M.F., the phase of which might be varied, was injected into the armature circuit.

By suitably varying the magnitude and time phase of the E.M.F. injected into the armature it is possible to obtain, at any speed, varying amounts of regenerated power.

The amount of power injected into the armature circuit is very small and the machine will regenerate 150 per cent of its full motor output when the power in the auxiliary circuit is 12 per cent of that in the main circuit. Fig. 12 shows the variation in regenerated power with speed for various auto-transformer tappings and for the different types of injection mentioned in the subjoined notes.

The particulars of the curves shown in Fig. 12 are as follows:—

Curve	Injected E.M.F. as percentage of V_S	Time phase-relationship between injected E.M.F. and V_S	Power factor of regenerated power at 450 r.p.m.
A	Zero	—	0·410
B	5 %	Phase opposition	0·336
C	10 %	Phase opposition	0·303
D	5 %	Quadrature lagging	0·520
E	10 %	Quadrature lagging	0·553
F	30 %	Quadrature lagging	0·627

In conclusion, the author wishes to thank Professor E. W. Marchant, D.Sc., for the many helpful suggestions put forward during the preparation of this paper.

INSTITUTION NOTES.

Council for the Year 1924–1925.

The scrutineers appointed at the Annual General Meeting on the 8th May, 1924, in connection with the ballot to fill the vacancies which will occur in the Council on the 30th September next, have reported to the President that 506 ballot papers were returned, of which 33 were spoiled, and that the result of the ballot is as follows :—

President : Mr. W. B. Woodhouse.

Vice-Presidents : Mr. S. Evershed and Mr. A. Page.

Hon. Treasurer : Mr. P. D. Tuckett.

Ordinary Members of Council : (Members) Mr. W. E. Highfield, Mr. Herbert Jones, Mr. B. Longbottom and Mr. E. H. Shaughnessy, O.B.E. ; (Associate) The Viscount Falmouth.

The ballot on this occasion was purely formal, no nominations other than those made by the Council having been received.

The Council for the year 1924–1925 will therefore be constituted as follows :—

President.

W. B. Woodhouse.

Past-Presidents.

A. Siemens.	Sir John Snell.
Col. R. E. Crompton, C.B.	C. P. Sparks, C.B.E.
Sir Henry Mance.	C. H. Wordingham, C.B.E.
J. Swinburne, F.R.S.	R. T. Smith.
Sir R. T. Glazebrook, K.C.B., D.Sc., F.R.S.	Ll. B. Atkinson.
	J. S. Highfield.
W. M. Mordey.	F. Gill, O.B.E.
S. Z. de Ferranti, D.Sc.	A. Russell, D.Sc., F.R.S.

Vice-Presidents.

Sir James Devonshire, K.B.E.	A. Page.
S. Evershed.	A. A. C. Swinton, F.R.S.

Honorary Treasurer.

P. D. Tuckett.

Ordinary Members of Council.

J. W. Beauchamp.	B. Longbottom.
R. A. Chattock.	S. W. Melsom.
F. W. Crawter.	G. W. Partridge.
Captain J. M. Donaldson, M.C.	Col. T. F. Purves, O.B.E.
	W. R. Rawlings.
D. N. Dunlop.	P. Rosling.
K. Edgcumbe.	E. H. Shaughnessy, O.B.E.
The Viscount Falmouth.	
A. F. Harmer.	Prof. W. M. Thornton, O.B.E., D.Sc.
W. E. Highfield.	
Herbert Jones.	

and

The Chairman and immediate Past-Chairman of each Local Centre.

I.E.E. Regulations for the Electrical Equipment of Buildings.

The Eighth Edition of the "I.E.E. Regulations for the Electrical Equipment of Buildings," formerly the "I.E.E. Wiring Rules," referred to in the Report of the Council for the year 1923–1924 (see page 530) has been approved by the Council and copies may be purchased at the offices of the Institution or from the publishers, Messrs. E. and F. N. Spon, Ltd., 57, Haymarket, London, S.W. 1. at the following prices: bound in cloth, 1s. 6d. net (or 1s. 8d. post free); bound in paper covers, 1s. net (or 1s. 2d. post free).

In the Report of the Council for the year 1920–1921 (*Journal I.E.E.*, 1921, vol. 59, page 348) it was stated that the Council proposed to arrange for the draft Rules to be discussed at meetings in London and at the Local Centres before they were finally issued. The Council have, however, been obliged to decide, with regret, that this course is impracticable. It has proved difficult to reach unanimous agreement upon the revised Regulations by a Committee consisting of a very large number of members representing diverse interests, and it has only been possible by numerous mutual concessions to issue a set of Regulations agreed by all these interests. The revised Regulations could not therefore at the present stage be altered in principle, and for this reason in the opinion of the Council no useful purpose would have been served by an open discussion of the Regulations before their publication.

Students' Premiums.

The following premiums, each of the value of £10, have been awarded by the Council for papers read before the Students' Sections during the past session :—

Author	*Title of Paper*	*Where read*
N. B. Hill	"Alternators for Operation on a Transmission Line"	Liverpool
A. I. Macnaughton B.Sc. (Eng.)	"Some Notes on Insulating Papers"	Glasgow
V. Mitchell	"The Electrical Equipment of Railways, with Special Reference to Signalling"	Bradford
O. Morduch and B. L. Metcalf	"Electrification Schemes in Russia"	Manchester
B. Nuttall	"Automatic Protective Apparatus for Alternating Current Circuits"	Manchester
A. C. Warren, B.Sc.	"Northolt Radio Station"	London

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 June–25 July, 1924:—

	£	s.	d.
Adcock, F. W. D. (Leigh-on-Sea)		5	0
Davie, J. F. (London)		10	6
Edgar, F. J. (London)		10	0
Evans, G. J (Pontypridd)		2	6
General Electric Company, Ltd. (London)	21	0	0
Gerrard, F. J. (London)		5	0
Gothard, B. W. (Farnborough, Hants) ..		5	0
Green, F. W. (Melbourne, Australia) ..		10	6*
Grover, E. E. (Hexham)		5	0
Haley, W. E. (Shipley)		5	0
Hasdell, J. S. (London)		5	0
Hirst, H. (London)	10	10	0
Lawson, F. A. (London)		5	0
Redman, W. (Shipley)		5	0
Roberts, A. J. (London)		5	0
Veale, F. L. (London)		10	0
Vignoles, E. B. (Streatley-on-Thames) ..	2	2	0
Williams, E. (London)		5	0
Willson, L. F. (London)		3	6

* Annual Subscription.

Accessions to the Reference Library.

STARLING, S. G. Electricity and magnetism for advanced students. 4th ed. 8vo. 618 pp. *London*, 1924

STONE, P. M. Electricity and its application to automotive vehicles. 8vo. 860 pp. *London*, [1924]

STRECKER, K. Hilfsbuch für die Elektrotechnik. Unter Mitwirkung namhafter Fachnegossen, bearbeitet und herausgegeben von Dr. K. S. 9e Aufl. 8vo. 671 pp. *Berlin*, 1921

TERRELL, T. The law and practice relating to letters patent for inventions. 6th ed., revised by C. Terrell and A. Jaffé. 8vo. 645 pp. *London*, 1921

TOCHÉ, C. La radiotéléphonie. Préface de M. le Général Ferrié. sm. 4to. 104 pp. *Paris*, 1922

VERBAND DEUTSCHER ELEKTROTECHNIKER. Regeln für die Bewertung und Prüfung von elektrischen Maschinen. (R.E.M. 1923). Sonderabdruck aus Vorschriften und Normen des V.D.E., 11. Auflage. 8vo. 37 pp. *Berlin*, 1923

—— Vorschriften und Normen des Verbandes Deutscher Elektrotechniker. Herausgegeben von dem Generalsekretariat des V.D.E. 11e Aufl. Nach dem Stande am 31 Dez. 1922. 8vo. 564 pp. *Berlin*, 1923

WADE, C. F. A manual of fuel economy. 8vo. 152 pp. *London*, 1924

WALKER, M., *D.Sc.* The control of the speed and power factor of induction motors. la. 8vo. 151 pp. *London*, 1924

THE FUTURE OF MAIN-LINE ELECTRIFICATION ON BRITISH RAILWAYS.

By Lieut.-Colonel H. E. O'BRIEN, D.S.O., Member.

(*Paper first received 4th February, and in final form 10th March,* 1924; *read before* THE INSTITUTION *27th March, before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE *17th March, before the* NORTH-WESTERN CENTRE *18th March, before the* NORTH-EASTERN CENTRE *24th March, and before the* SOUTH MIDLAND CENTRE *2nd April,* 1924.)

SUMMARY.

Extensive main-line electrification has hitherto been considered to be a rather remote possibility in Great Britain, it being supposed that the capital expenditure involved and the price of current would be prohibitive. The great superiority and simplicity of the electric as compared with the steam locomotive as a machine has not been realized. The author shows that the probable density of traffic in ton-miles on the main railway arteries is so great that the cost of energy, including all capital charges, will not be prohibitive, also that the cost of the electric locomotives will not be a capital charge, and, further, that when the reductions in the cost of locomotive operation and maintenance (due to the simple construction of the electric locomotive) are taken into account, the total cost of locomotive operation is substantially less for electricity than for steam. The conclusion is that though it has only been possible to base the argument on general statistics, the problem merits closer and more immediate investigation than has hitherto been accorded to it.

The presentation of another paper on this subject must be prefaced by an apology from the author for presuming again to approach a subject which has been dealt with so recently and so ably by other writers. The matter is, however, of such importance to both the railway companies and the electrical industry that it is desirable to reiterate the arguments in favour of main-line electrification in a form which, it is hoped, will appeal as much to railwaymen as to electrical engineers.

The author hopes to show that:—

(1) The cost of operating suburban electrical services is less than the average cost of the general steam-operated services, and very much less than that of a steam-operated suburban service;

(2) The modern electric power station is now able to produce electrical energy at such a price that the cost of current supplied to an electric locomotive is but slightly higher than the cost of coal supplied to a steam locomotive; and, finally,

(3) The design of electric traction motors and control equipment has made such advances that the total cost of operating electric locomotives is far below the similar cost for steam locomotives.

It is further sought to show how the relative density of traffic affects the cost of current, and that there is strong probability that on the main arteries of traffic the density is substantially higher than on the suburban lines already electrified.

An examination of the problem is most conveniently divided into two parts: first, the consideration of the relative value of the electric locomotive as a tractor as compared with the steam locomotive; and secondly, how that value is affected by the cost of electrical energy supplied to the electric locomotive in comparison with the cost of coal supplied to the steam locomotive.

In effect, the subject should be considered, first, from an almost purely railway standpoint, secondly, from an almost purely electrical standpoint, and, thirdly, in relation to the density of traffic. The solution of the question of the economic density of traffic which will give an adequate return on the capital expenditure involved is the key to the future of the electrification of British main lines.

Mr. Roger Smith * has already dealt with the subject, using the number of locomotives per mile of track as a basis, and Mr. H. Parodi of the Paris-Orleans Railway in a recent paper † has also used as a basis the coal consumption per mile of track. It appears to the present author, however, that for British conditions the subject may be more clearly considered by using the engine-mile as a basis, as this is a figure readily obtainable and already considerably used for comparative purposes in railway work.

For the benefit of those unacquainted with railway working it may be explained that the engine mileage of a system is the actual number of miles run by all the steam tractors of that system in a given period whether hauling freight, passenger or other trains, or without trains. Statistics of engine mileage are published in some detail monthly and annually by the Ministry of Transport; statistics of train-miles are also published, these being engine-miles run in connection with the haulage of freight or passenger trains but excluding shunting, light running and trains operated for service purposes.

It is true that the engine-mile, though a concrete fact, has a somewhat indefinite meaning, inasmuch as no value of work done attaches to it. The ton-mile is really almost as indefinite in this sense as the engine-mile, as in both cases all reference to the time factor is omitted. The average time factor or speed of trains can, however, be taken as a constant for any English main line, but the average weight of train, as will be seen later, varies somewhat. In considering averages (a method which is forced on the investigator by the existing statistical methods of English railways) deductions may, however, be safely drawn as to the probability of higher values than the average existing, when it is known that a large proportion of the whole represents lower values—the speed and weight of trains on branch lines will obviously be less than on the main line.

It will be necessary to consider quantitative figures, for the essence of the problem is financial, and the

* Société des Ingénieurs Civils de France (British Section), Presidential Address, 1923–24.

† "Electrification Partielle du Reseau de la Compagnie du Chemin de Fer d'Orleans," *Bulletin de la Société Française des Electriciens*, ser. 4, vol. 3, No. 23.

decision whether or not to electrify portions of the British main lines will rest with financiers rather than with technical experts.

At the outset it will be convenient to consider in some detail the disabilities of the existing method of railway haulage by steam in comparison with the advantages—and also the limitation of those advantages—which are to be gained by a change of method.

The steam locomotive as it exists to-day is in all essentials the machine designed by Stephenson, much enlarged and constructed with the improved materials now available.

The design has inherent disadvantages due to the constricted space available for the steam generator, which entails extraordinary rates of combustion, and for the low-speed prime mover, which entails high pressures on small bearing areas exposed to dirt and moisture. The machine is further very susceptible to weather conditions and variations in the quality of the fuel supply. The principal advantage of the steam locomotive lies in the independence of the tractive units so that the failure of one has no direct effect on the rest, while there is unlimited freedom of movement on rails so long as the machine has a supply of coal and water.

The cost of maintenance is therefore high but is probably decreasing, though very slowly, due to better appreciation by the operating staff of the value of close analysis of the causes of failure and by continued progress in the quality of the material used in construction.

The disabilities of the steam tractor may be briefly set out as follows :—

(1) Inability to give continuous service without considerable idle intervals.
(2) High cost of repairs.
(3) Low thermal and mechanical efficiency, and small range of maximum efficiency.
(4) Limited tractive capacity per unit.
(5) High weight per continuous draw-bar horse-power available.
(6) Liability to failure in service.
(7) Susceptibility to weather conditions.
(8) Irregularity of turning effort.
(9) Necessity for operation of each unit by two skilled men.
(10) Rapid increase of haulage cost with increased weight and speed of trains, particularly on gradients.
(11) Overload capacity cannot be given instantaneously and is limited.
(12) Exact allocation of current costs between various classes of traffic.

The limitation on the maximum continuous draw-bar capacity in horse-power of the steam tractor, results in a general use of the machine at or near its continuous capacity, and this, combined with the other factors previously referred to, is the principal cause of the high cost of maintenance. It is a well-known phenomenon of railway operation that just as fast as the chief mechanical engineer's department designs more powerful machines, so the increased capacity is absorbed, or more than absorbed, by the traffic department.

Before entering into the comparative advantages of the electric tractor in relation to the above, it is necessary to examine very briefly other possible improved forms of tractor.

The turbo-electric locomotive may be quickly dismissed : the weight per draw-bar horse-power is much higher than that of the steam locomotive, it requires more skilled attention, the first cost must be higher than that of an electric locomotive and very much higher than that of a steam locomotive, and a crew of two if not of three men is required. The possible advantages are a saving in fuel and, perhaps, reduced boiler repairs due to condensate being available for a portion of the boiler feed. The straight turbo locomotive seems to have more possibilities, but here again only a saving in fuel and a possible saving in boiler repairs can be offset against increased weight and complication.

The internal-combustion locomotive is still in swaddling clothes ; suffice it to say that only prolonged and expensive research shared by a large railway company and a manufacturing firm with ample resources is likely to result in the production of a practical tractor of 800 to 1 500 draw-bar horse-power capable of continuous service in traffic. If, and when, such a machine is produced costing no more than a steam locomotive, with a fuel consumption in money value of less than half that of the steam tractor, a possibility of multiple operation with a single crew and a demonstrated lower cost of repairs, then the electric locomotive will have a serious rival.

The electric locomotive compared purely as a tractor with its steam rival, leaving out of account all question of the cost of fuel or energy supplied for a given service, has the following advantages :—

(1) Capacity for almost continuous service in traffic.
(2) Low cost of repairs.
(3) High tractive capacity per unit.
(4) Low weight per continuous draw-bar horse-power available.
(5) Reliability in service.
(6) Complete independence of weather conditions.
(7) Even turning effort.
(8) High mechanical efficiency and large range of maximum efficiency.
(9) Possibility of operation as a unit or in multiple by one man.
(10) Reduction of signal movements and occupation of tracks due to elimination of necessity for turning and movements for obtaining coal and water and daily visits to sheds.
(11) Much greater flexibility of wheel base.
(12) Large overload capacity available instantaneously.

The disadvantages are the number of units which may be immobilized by a failure of energy supply, and the dependence of each unit for mobility on contact with the electrical distribution system of the track.

In a mixed system of electric and steam traction a further disadvantage is the necessity for changing from

steam to electric traction at the terminal points of the steam section. The economic length for electrification may not coincide with the natural economic length of run for a steam locomotive.

The question of the change of locomotive from steam to electric, and vice versa, has an important bearing on the financial aspect of main-line electrification. While such changes may be almost eliminated when a complete scheme of electrification has been carried out, the impossibility of dealing with an electrification of 1 000 or 1 500 track-miles except by stages, together with the fact that in general the maximum economic length of run of a steam locomotive is not more than 160 miles, may necessitate a considerable expenditure in the initial stages on temporary accommodation for steam locomotives at the temporary termination of each stage; nor will the expenditure be confined to locomotive housing alone, as accommodation will have to be provided temporarily for a large number of staff who will be displaced.

While given the conditions necessary for a successful electrification, viz. cheap current and requisite density of traffic, a limited scheme might not be a financial success, at the same time it will be clear that the full economies indicated in the paper could not be realized if it were necessary to retain a considerable percentage of the steam tractors in use with their concomitant services for water, coal, cleaning, etc.

Before considering the probable costs of main-line locomotive operation, force will be given to the arguments to be used subsequently by a comparison of the costs of steam and electric suburban services.

Suburban services operated at high schedule speeds with frequent stops are admittedly more costly to work than the average services on the main lines and branches of a railway; consequently, if a comparison be made between the average cost of operation per steam engine-mile on a typical main line and its branches and the cost of operation of suburban electrifications, the comparison will be of a very conservative nature by no means unduly favourable to electrical operation.

The average mileage per annum per steam locomotive in stock on the largest British system is approximately 26 000 miles per annum for passenger engines and 18 300 miles per annum for freight, the average being 21 100 miles per annum for the whole stock of 10 302 engines.

The cost of repairs per engine-mile, which is much lower than the cost of repairs per train-mile, varies on the various sections of the railway from 4·5d. to 6·9d., the average being 5·8d.

It must be borne in mind that these are averages and that large numbers of small tank engines and freight engines doing comparatively light work are included. The average mileage per annum is substantially less, and the cost of repairs per engine-mile is substantially heavier for the passenger and freight engines employed to haul the heavier trains on the main trunk routes, which would be the first to be electrified.

The existing methods of railway accounting do not, however, yield in a complete form such figures as would enable a definite quantitative statement to be made as to the amount by which such repairs are higher. These variations in repair costs are mainly due to differences in the weight and speed of the trains hauled, in the physical characteristics of the section such as curves and gradients, and in the purity of the water supply, which affects the boiler maintenance.

The average mileage per annum per train on the various suburban electrifications in Great Britain varies from 47 320 miles to 36 296 miles. This mileage per electric train per annum really is analogous to the mileage per steam locomotive per annum and may be used comparatively in considering relative costs.

The cost of repairs per train-mile varied from 2·1d. to 6·0d., the average being 4·18d., the variations in this case being due to differences in the design and age of the equipment and, to some small extent, to differences in the schedule speeds.

The steam locomotives probably averaged about 80 tons' weight in working order, and represented a present-day lowest market value of about £4 000 each and a maximum draw-bar horse-power of probably 800. The average steam locomotive of this weight would have been quite incapable of performing the electric suburban service, and the comparison really should be with locomotives weighing 120 tons, costing £8 400 each, and having a maximum draw-bar horse-power of 1 200.

The electric motor-cars, on the other hand, averaged about 60 tons for the tractor part of the train equipment including the weight of the motor bogies, cost about £8 000 per train at present market prices, and had a continuous draw-bar horse-power of 1 400.

Table 1 shows a comparison between

(1) The average cost of all steam services, passenger, freight and shunting, on a typical British railway system;

(2) The average cost of a high-speed electric passenger service;

(3) The estimated cost of operating the electric service by steam.

This conclusion is confirmed by Sir Philip Dawson in his paper on "Financial Prospects of Railway Electrification" where a diagram is given showing the relative costs per train-mile for suburban steam, main-line steam, and suburban electric services, the relative costs in 1921 being 61d., 51d., and 42d. per train-mile respectively on the London, Brighton and South Coast Railway.

It is therefore evident that, given a certain density of traffic, the cost of electric operation of suburban trains is markedly lower than the average cost of steam operation.

The above cost of steam-locomotive operation may now be compared with the probable cost if electric locomotives were substituted for main-line work. It is obvious on general principles that the result of this comparison should be much more favourable to electric operation than in the case of suburban traction dealt with above. The electrical equipment of the electric locomotives as a whole will be much less severely stressed on main-line work with comparatively long continuous runs than on the suburban work where

the frequent stops and high accelerations cause severe stresses on motors, control, gears and every other part of the equipment.

Before actually considering these figures it is desirable to give a brief comparison of the weights and performances of typical steam and electric locomotives. Table 2 gives a comparative statement of the leading dimensions for four typical freight and four typical passenger steam locomotives and for eight corresponding electric locomotives; these locomotives are also illustrated in Fig. 1, and some of their comparative speed and horse-power curves are shown in Fig. 2. The largest steam locomotives, freight and passenger, have not as yet been built, but are the largest practicable within the largest load gauge in this country; their range of action is extremely limited owing to the limitations of gauge and strength of bridges on many main lines. The electric locomotives are, with one exception, all built or building and would conform to the gauge and bridge strength of any main line in this country. It will be noted that, for the same weight, rather more than a 60 per cent increase in the continuous draw-bar horse-power is available. The latter fact has an important bearing on the cost of accelerating present services. Tests made on 500-ton passenger and 640-ton freight trains hauled by two steam locomotives run at average speeds over a line with heavy gradients, well in excess of the

TABLE 1.

Comparative Cost of Locomotive Operation of Main-line, Electric Suburban and Steam Suburban Services.

	Cost per engine-mile for typical British railway (steam) of large size with heavy traffic	Cost per train-mile of electric suburban services	Estimated cost of operation by steam of same service as electric
	d.	d.	d.
Superintendence ..	0·538	Included below	0·50
Wages connected with the running of engines	10·158	3·36	10·00
Fuel or current ..	7·842	17·41†	12·00‡
Water	0·331	Nil	0·50
Lubricants	0·352	0·08	0·50
Other stores	0·449	Nil	0·40
Repairs	6·910*	5·28	9·00
Miscellaneous ..	0·098	0·04	0·10
	26·678d.	26·17d.	33·00d.

* The cost of locomotive maintenance per engine-mile includes boiler renewals, overhead charges to cover supervision, clerical staff and office expenses, also workshop overhead charges, such as foremen's, clerks', and draughtsmen's wages, maintenance and renewal of machinery and plant including tools and general workshop expenses but excluding maintenance of buildings, rates and taxes, interest, depreciation, head office expenses and complete renewal of locomotives.

† Includes interest, depreciation and maintenance of power station, h.t. transmission, substations and track equipment.

‡ Tests made on the Liverpool and Southport electrification when a steam-hauled service was run to electric service schedule times showed the coal consumption to be 100 lb. of coal per engine-mile.

TABLE 2.—*Comparative Statistics of Steam and Electric Locomotives.*

Locomotive	Total weight: Empty	Total weight: In working order	Adhesive weight	Greatest weight per axle	Rated output at tread: 1-hour rating	Rated output at tread: Continuous rating	Length over buffers	Driving wheel diameter	Gear ratio	Maximum tractive effort at tread	Maximum sustained tractive effort at draw-bar	Maximum sustained power at draw-bar	Weight per draw-bar h.p.	Weight of greatest train haulable up 1 per cent grade continuously	Ratio: Col. 2 / Col. 14
Column no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	tons	tons	tons	tons	h.p.	h.p.	ft. in.	ft. in.		lb.	lb. *At 40 m.p.h.*	h.p.	tons	tons *At 40 m.p.h.*	
Passenger (*Steam*).															
(1) 2-8-2, 4-cylinder (proposed) ..	—	141·5	75·5	19·5	—	—	67 0	4 10	—	37 870	11 050	1 180	0·120	250	0·566
(2) 4-6-2, 3-cylinder G.N.R. ..	—	148·7	60·0	20·0	—	—	70 5⅛	6 8	—	29 840	10 420	1 110	0·134	230	0·647
(3) 4-6-0, 4-cylinder L.Y.R. ..	92·2	119·1	59·3	20·0	—	—	60 1¾	6 3	—	29 470	9 480	1 010	0·118	220	0·541
(4) 2-4-2, 2-cylinder L.Y.R. ..	52·5	66·5	39·3	19·7	—	—	39 2¼	5 8	—	24 580	7 410	790	0·084	190	0·350
(*Electric*).															
(5) 4-8-4 proposed design	—	116·0	72·0	18·0	3 000	2 600	55 9⅜	5 9	2·6	39 600	23 200	2 480	0·047	630	0·184
(6) 4-6-4 N.E.R.	—	102·0	55·5	18·5	1 800	1 300	53 6	6 8	—	28 000	8 120*	1 120*	0·091	170*	0·600
(7) 4-4-4-4 P.L.M.R. (Fr.)	—	116·0	71·0	17·7	2 270	1 870	65 7	5 3	3·9	39 800†	16 400	1 750	0·066	440	0·264
(8) 4-6-2 S.F.R. (Swit.)	—	90·8	54·4	18·2	2 070	1 770	48 2½	5 3½	2·57	30 500	15 700	1 680	0·054	440	0·206
Freight (*Steam*).											*25 m.p.h.*			*25 m.p.h.*	
(9) 2-10-0, 4-cylinder proposed design	97·0	134·0	80·0	16·0	—	—	63 8	4 10	—	53 300	21 090	1 410	0·095	570	0·235
(10) 2-8-0, 3-cylinder G.N.R. ..	—	118·9	67·4	17·6	—	—	61 4¾	4 8	—	36 500	14 370	960	0·124	370	0·322
(11) 0-8-0, 2-cylinder L.Y.R. ..	77·8	107·7	66·2	17·4	—	—	59 1¾	4 6	—	34 050	13 240	880	0·122	340	0·316
(12) 0-6-0, 2-cylinder L.Y.R. ..	57·8	72·6	46·5	17·0	—	—	48 9	5 1	—	26 090	12 600	840	0·086	350	0·207
(*Electric*).															
(13) 2-6-6-2 P.L.M.R. (Fr.)	—	114·3	94·5	15·8	1 970	1 680	69 6	4 7	4·47	53 000†	21 660‡	1 620‡	0·071	580‡	0·196
(14) 2-6-6-2 P.L.M.R. (Fr.)	—	112·4	94·5	15·8	2 170	1 720	70 10¾	4 7	4·35	53 000†	22 280‡	1 660‡	0·068	600‡	0·187
(15) 4-4 Midi R. (Fr.)	—	69·4	69·4	17·3	1 400	1 000	38 10	4 7	5·066	38 900†	15 390	1 030	0·067	440	0·158
(16) P.O.R. (Fr.)	—	63·0	63·0	15·8	1 700	1 300	40 10¾	4 5	—	35 300†	18 080	1 210	0·052	520	0·121

* At 51·5 miles per hour. † Taken as one-fourth the adhesive weight. ‡ At 28·0 miles per hour.

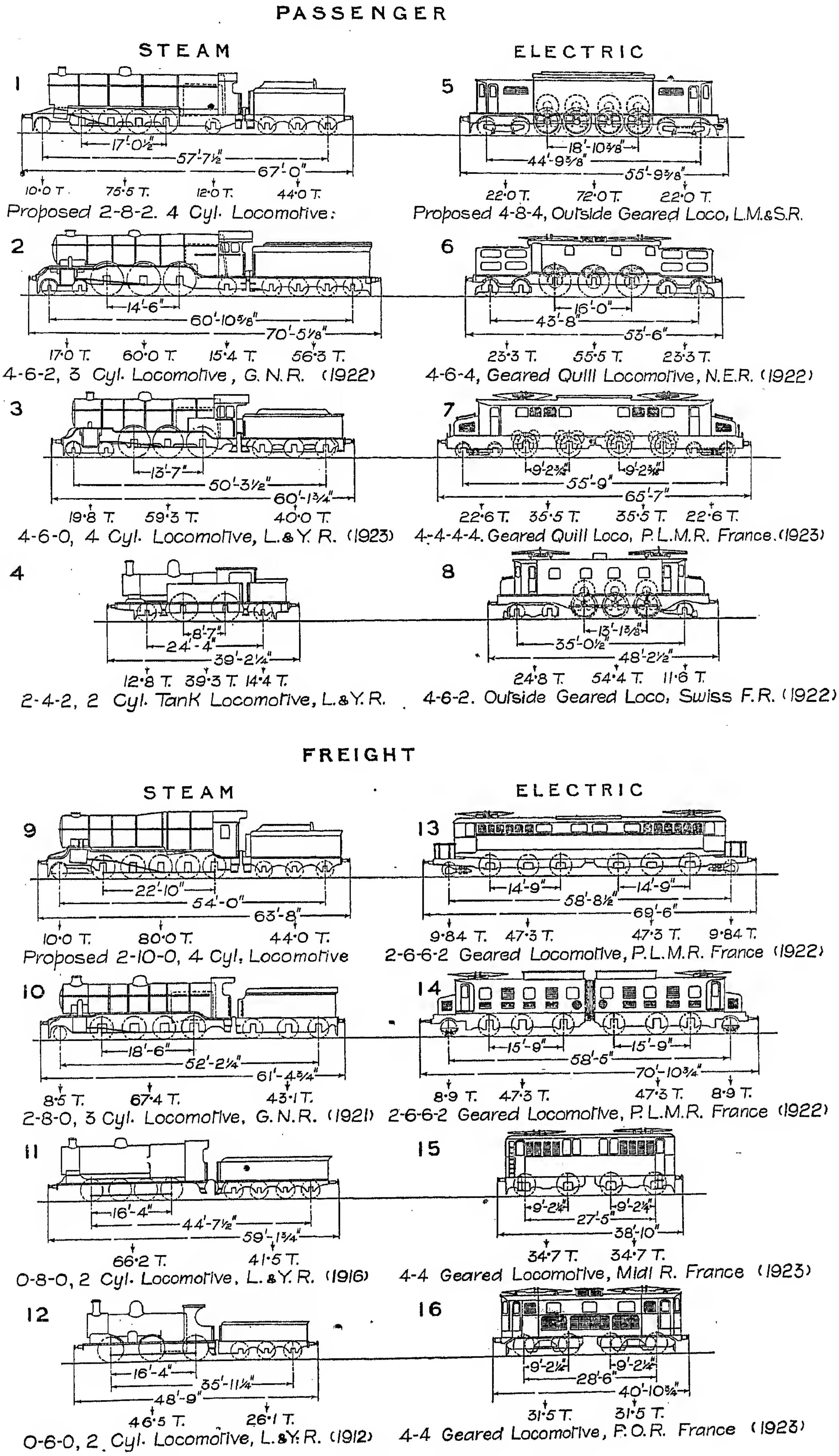

FIG. 1.—Comparative diagram of steam and electric locomotives.

average booked schedule speeds and yet without increase of maximum speed, showed that as soon as the maximum draw-bar horse-power required exceeded that obtainable from one locomotive, the ratio of both maximum and mean draw-bar effort to adhesive weight became very large.

The weight of the steam locomotives was nearly 50 per cent of the weight of the train hauled in the case of the passenger train, and 37 per cent in the case of the freight train; a slight increase in either weight or speed up the gradients would have made these figures 72 per cent and 56 per cent respectively. As the maximum draw-bar pull did not exceed from 8 to 9 tons for the mean speed, an electric locomotive of a total weight of 116 tons and 72 adhesive tons available for traction would have met all requirements. The necessary draw-bar horse-power can be produced by an electric locomotive of this weight.

The results of these tests are shown in Figs. 3 and 4. The aggregate maximum draw-bar pull of the two locomotives used was 27 tons, and the adhesive weight available for traction was 118·5 tons.

The maximum draw-bar horse-power recorded over one minute on the tests was 2 015 in the case of the freight train, and 1 921 with the passenger train. With the freight train, excluding gain due to increase of maximum speed on the level and down hill, the overall time for the 90 miles was reduced by 11 per cent and with the passenger train 10 per cent was gained, this saving in both cases being due solely to faster uphill running. Such faster speeds on up gradients can be attained by the steam locomotive only at the expense of heavy fuel consumption and exceptional wear and tear; with an electric locomotive much better results can be obtained.

Take the case of an up grade of 0·75 per cent, 30 miles in length, and a train of 750 tons trailing; the resistance due to the gradient is 17 lb. per ton, whilst the resistance for a goods train at 20 miles per hour is 8 lb. per ton, and at 40 m.p.h. is 15 lb. per ton, the total resistance therefore being 25 lb. per ton and 32 lb. per ton respectively. The train-resistance curves on which these and other figures in the paper are based are shown in Fig. 5. If the draw-bar horse-power required in the first instance is 1 000, in the second it is 2 560, but the time for ascending the gradient is 90 minutes in the first instance as compared with 45 minutes in the second. The horse-power-minutes are respectively 90 000 and 115 000, the draw-bar pulls being 18 750 lb. and 24 000 lb. respectively. Half the time is thus saved with an expenditure of only 27·8 per cent more energy and only 28 per cent increase in draw-bar pull.

The 750-ton train at 40 m.p.h. on this gradient could be dealt with only by a combination of three steam locomotives employing a crew of six men and weighing 348 tons, or nearly 50 per cent of the weight of the train. An electric locomotive weighing 116 tons and operated by a single man could perform the same duty with ease.

The gross weight of the steam-hauled train would thus be 1 098 tons, whilst that of the electrically hauled train would be only 866 tons. Assuming from Lawford Fry's curve that the resistance of the steam locomotive is 22 lb. per ton and that the electric locomotive has

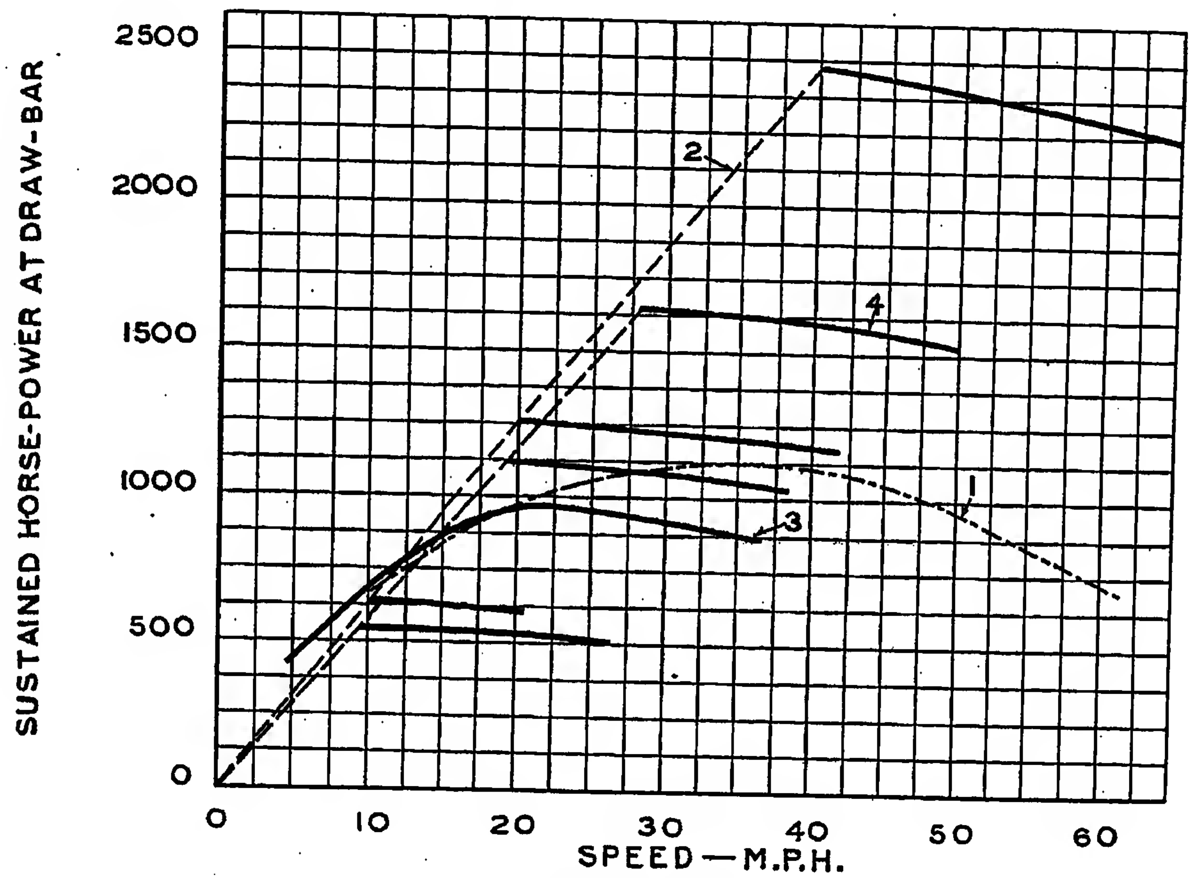

FIG. 2.

Curve 1. (Steam) 4–6–2 3-cylinder passenger locomotive (G.N. Rly.).
Curve 2. (Electric) 4–8–4 passenger locomotive (L.M. and S. Rly.).
Curve 3. (Steam) 2–8–0 3-cylinder freight locomotive (G.N. Rly.).
Curve 4. (Electric) 2–6–6–2 freight locomotive (P.L.M. Rly.).

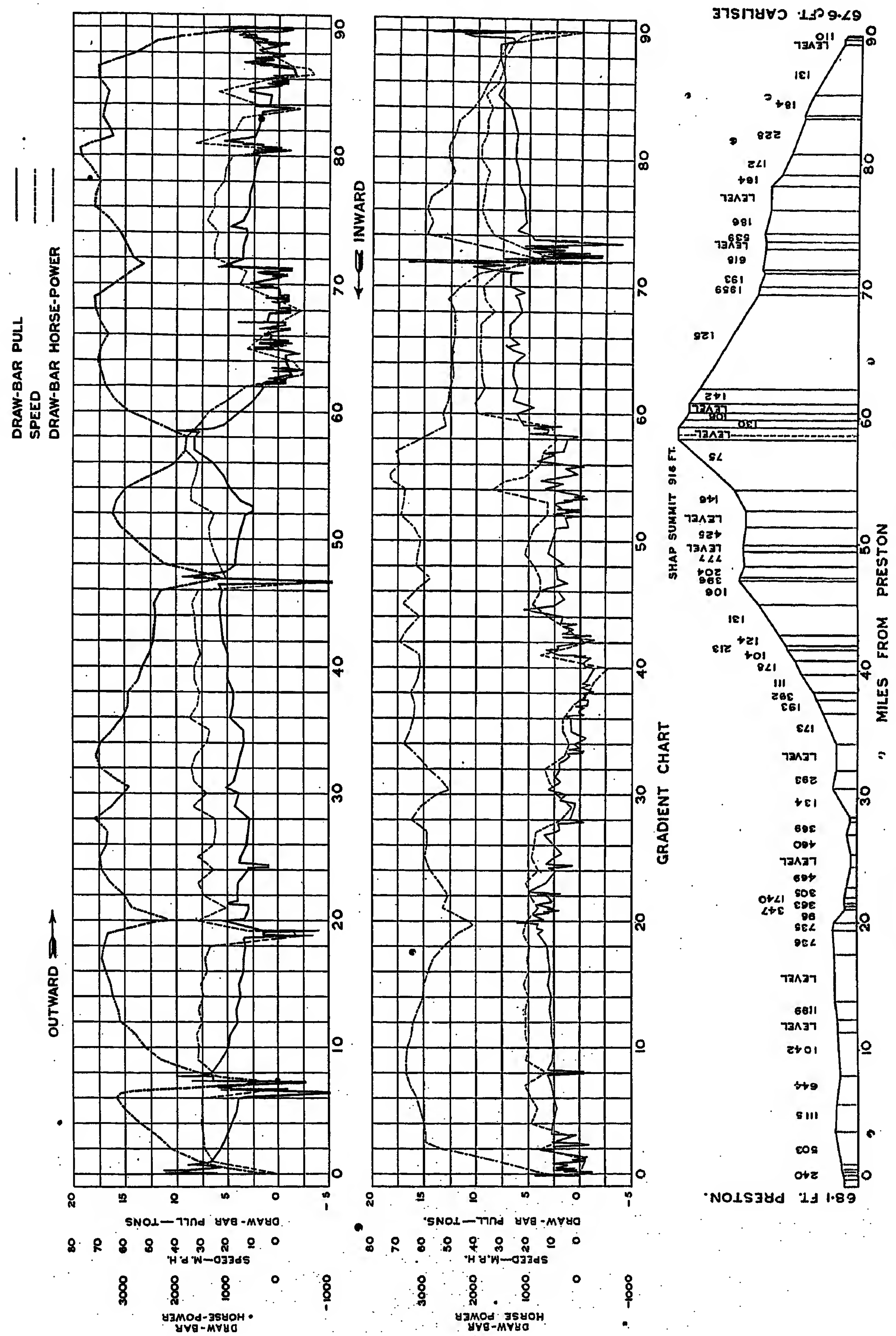

FIG. 3.—Double-headed run with 500-ton passenger train over 90-mile section of main line.

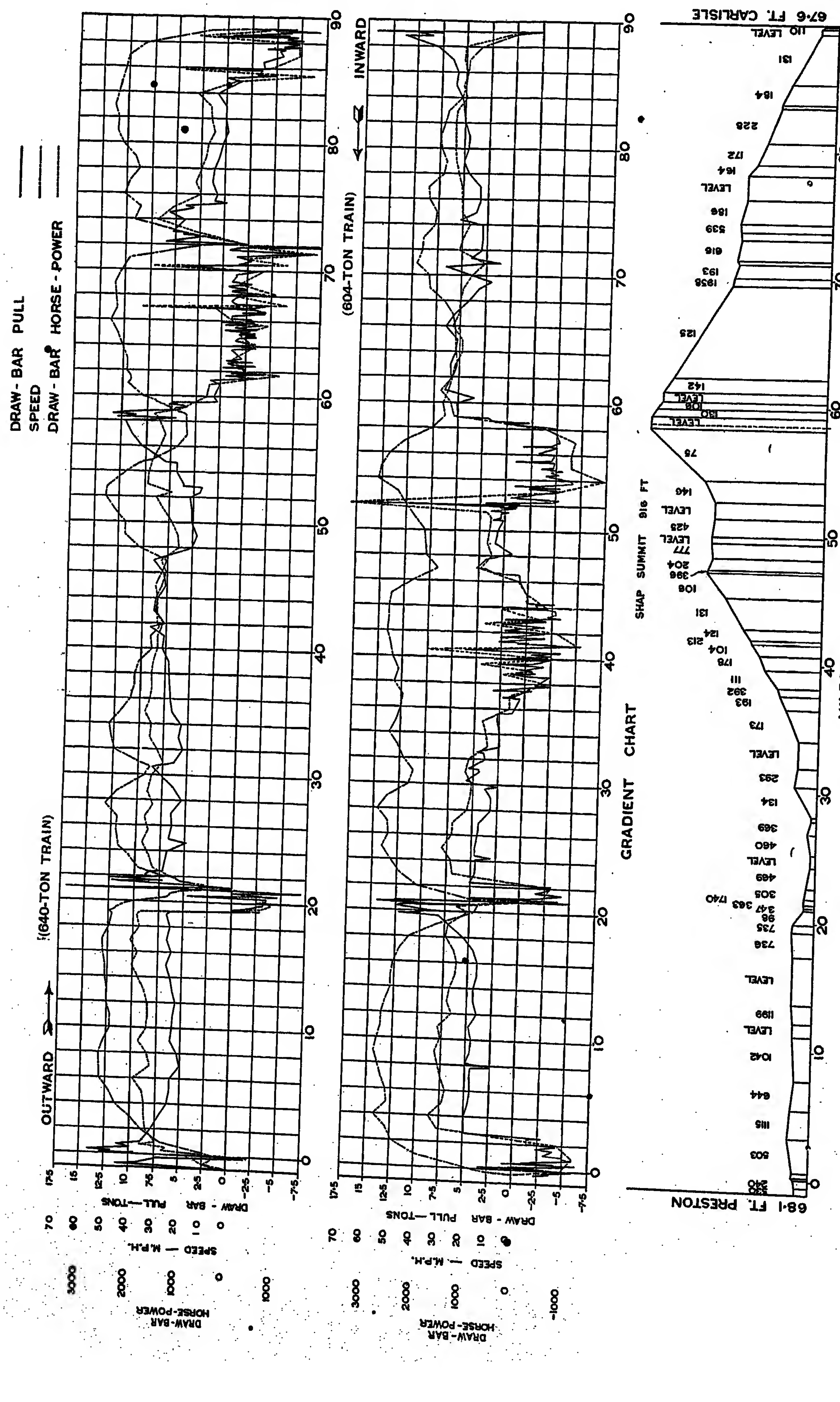

FIG. 4.—Double-headed run with heavy freight train over 90-mile section of main line.

a resistance of 10 lb. per ton, the gross h.p.-minutes for the steam train will be 166 000, as against 130 000 for the electrically hauled train, i.e. the steam-hauled train requires an increased energy input of 27 per cent. The cost of the three steam locomotives would be about £24 000 and the cost of the electric locomotive would be about £16 000. On arrival at the end of a 90-mile run including this gradient the steam locomotives would have to be changed for fresh ones, but the electric locomotive would be at once ready for another similar run. The electric locomotive would field. On this basis in a run of 100 miles containing 20 miles of 1 in 300 up grade and 20 miles of 1 in 300 down grade, excluding any gain due to acceleration at starting, about 20 minutes could be gained, 10 minutes due to 20 per cent higher speed on the level and 10 minutes due to $33\frac{1}{3}$ per cent higher speed on the grade.

Taking the same comparison with a 2–8–0 steam locomotive, the curves for which are also given, the steam-hauled speeds with 1 000-ton freight train would be 28 m.p.h. on the level and 18 m.p.h. on the grade. The same electric locomotive would give 43 m.p.h. on

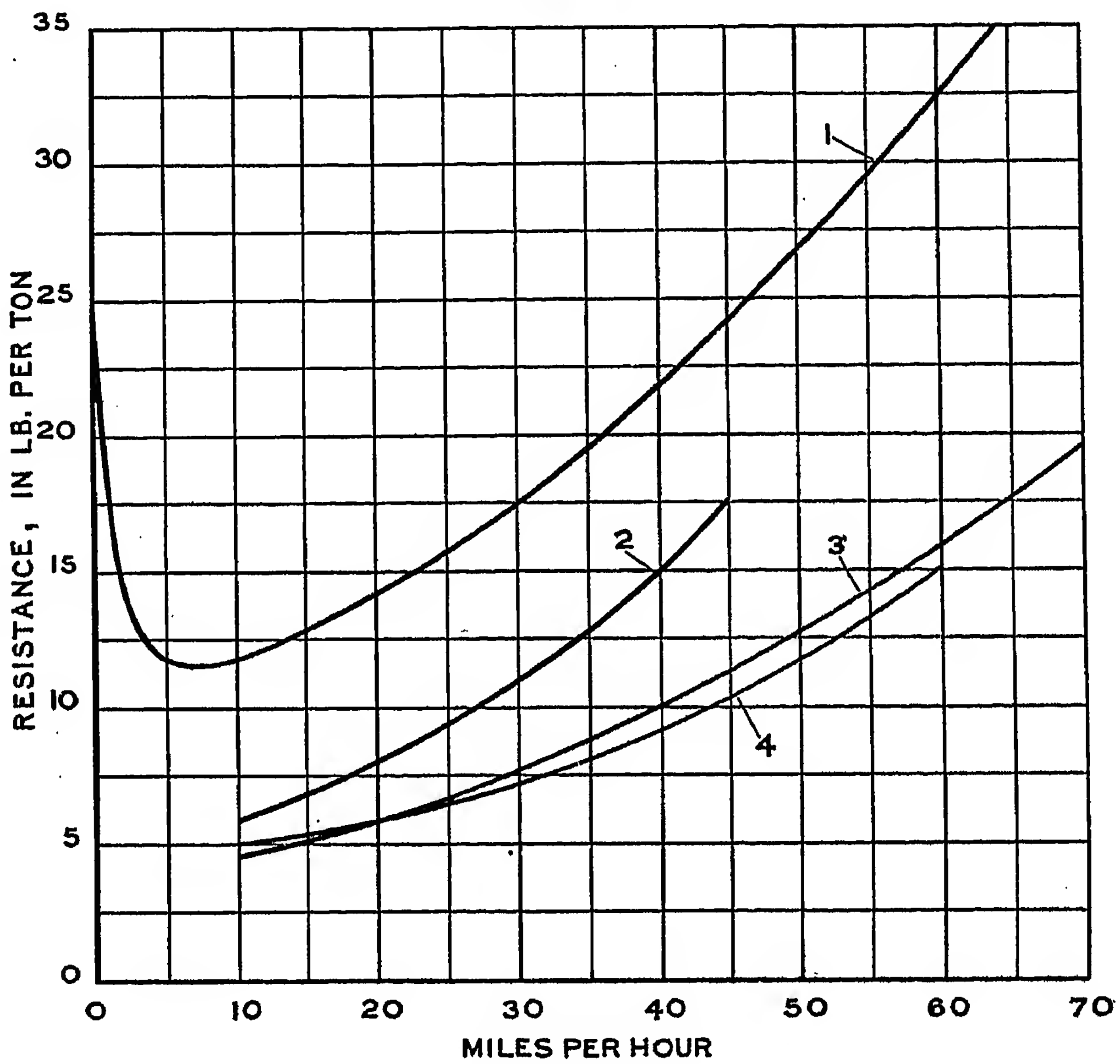

FIG. 5.—Resistance curves.

Curve 1. Steam locomotive and tender (Lawford Fry).
Curve 2. Goods train-10 ton wagon stock (L. H. Fry).
Curve 3. Electric locomotive as a vehicle.
Curve 4. 435-ton passenger-train tests (L.M. and S. Rly.).

be equally efficient when working at the rate of 3 000 h.p., its one-hour rating, or at 750 h.p. if required to work a lighter train back, while the steam locomotives would be at a grave disadvantage in this respect.

Examination of curves given in Mr. Roger Smith's paper on "Some Problems of Railway Electrification" shows that the Great Western 4–6–0 steam locomotive referred to in this paper would have a speed of 55 m.p.h. on the level and 40 m.p.h. on a 1 in 275 grade with a 500-ton train. The speeds of Sir Vincent Raven's 2–C–2 electric locomotive with the same weight of train would be from 56 to 70 m.p.h. on the level and 47 to 58 m.p.h. on the grade, according to the shunt the level with full field and 39 m.p.h. on the grade. Even if the 20 miles of grade were continuous, this 20 miles would take only 30 minutes and the horse-power given out by the motors would be 2 350, which would be within their thermal capacity for this time.

The result of experience on suburban lines of the London and North Eastern Railway in this country, and on numerous electrified railways elsewhere (see Appendix 1), shows that the cost of repairs to an electric locomotive is from one-third to a quarter of that of a steam locomotive per engine-mile; and the same reduction in cost occurs in connection with sub-

sidiary services rendered at steam sheds, such as cleaning, coaling, washing-out boilers, etc.

Owing to the simplicity of construction of the electric locomotive and the high degree of excellence of manufacture now attainable, it is probable that the average mileage obtainable between general repairs to the electric equipment will exceed 200 000 miles. The facts that the London and South Western Railway on their suburban equipments and the London and North Eastern on their freight locomotives have never rewound an armature or field coil during 7 years' operation, and that the life of the modern commutator is at least 750 000 miles, are strong indications that the forecast given of the cost of repairs is correct.

The turning and changing of tyres and axle brasses, the renewal of brake blocks and the repairs to auxiliaries such as vacuum pumps, will be the principal causes of an interruption to continuity of service for any appreciable period. As neither these nor motor repairs will necessitate the return of the locomotive to the main repair shops, the capacity of these for steam-locomotive repairs will be considerably increased. The truth of the assertion is more evident if it be considered that 90 per cent of the cost of steam-locomotive repairs arises from the boiler or from crank axles, wheels and frames due to the reciprocating and variable stresses imposed on these latter.

Further, the experience of suburban electric services enables it to be said with absolute certainty that an electric locomotive can be available for traffic for 23 hours out of 24, and that a fortnightly examination of the electrical equipment will be sufficient.

The electric locomotive will therefore be capable of an annual mileage of 40 000 to 50 000 miles per annum, as compared with an average of about 20 000 miles for a steam locomotive; in fact, the mileage possibilities are only limited by the traffic requirements and the extent to which engine workings can be arranged to permit of continuous service. Universal experience indicates that one electric locomotive will at least perform the duty of two steam locomotives (see Appendix 1). At all times, and especially in foggy weather or at night, traffic movement will be greatly facilitated by the absence of any necessity for engines going out of service for coal, water, cleaning fires, tubes and smoke-boxes, or for turning. The liability to failure of the electric locomotive is also much less than that of the steam locomotive. It may be argued that the freedom of units from failure is counterbalanced by the possibility of failure of current supply, so that in the aggregate the time lost in this respect will be the same if not greater. The reliability of the electrical supply equipment is, however, so great to-day that the most modern suburban electrifications never suffer more than momentary interruptions due to circuit breakers operating.

The total cost of enginemen's wages will also be substantially reduced. Engine duties which represent time during which an engine is not in movement owing to its being required by its crew for examination, coaling, watering or cleaning fires, etc., account for 15 per cent of the enginemen's hours in passenger service and 12 per cent in freight service. These engine duties will be to a great extent eliminated with electric locomotives.

The necessity for double crews on double-headed trains also disappears, and with this from 3 to 5 per cent of the total cost of enginemen's wages.

The further absence of any real need for a second skilled man on an electric locomotive, at least for shunting engines and multiple-unit trains, combined with the better utilization of the machine which should be possible by re-arrangement of the engine workings, should enable the total cost of enginemen's wages to be reduced by 33⅓ per cent.

Dealing with the remaining costs, that for water disappears, that for lubricants will be at least halved owing to the disappearance of cylinder oil and oil for reciprocating parts, and clothing and other stores will also be halved owing to the greater cleanliness of the electric locomotive.

On a typical suburban electrification which has been in operation for nearly 20 years the cost per train-mile was:—

Lubricants	0·033d.
Other stores and clothing	0·030d.
Other wages at sheds	0·640d.
	0·703d.

The comparative costs are shown in Table 3, which compares the costs on one of the former railway systems carrying heavy main-line traffic and the estimated costs of electric locomotive operation for the same traffic.

TABLE 3.

Cost of Operation and Maintenance per Engine-Mile, excluding Locomotive Renewals and Fuel or Energy.

	Year 1922 (Steam)	Estimated for electric locomotive	
	d.	d.	
Superintendence	0·538	0·538	No change
Wages: Enginemen's	7·500	5·000	33⅓% reduction
Repairs	6·910	2·300	66 % reduction
Water	0·331	0·000	Eliminated
Lubricants ..	0·352	0·120	66 % reduction
Other stores, and clothing	0·449	0·224	50 % reduction
Miscellaneous ..	0·098	0·098	No change
Other wages at sheds	2·658	0·620	75 % reduction (approx.)
	18·836d.	8·900d.	

On locomotive operation costs alone, excluding fuel, and almost quite independently of the density of traffic, there should be an economy of nearly 10d. per engine-mile.

The average density of traffic, which seriously affects the cost of the electric current supplied to the locomotive, would, however, preclude the realization of such a large economy in practice.

Before passing to the consideration of the cost of energy and how this modifies the very real economy affected by the electric tractor as a substitute for the steam tractor, some other points must be dealt with.

The weight of the main-line passenger and freight trains in this country is comparatively small. On a certain 100-mile section of the London, Midland and Scottish Railway with heavy gradients, an examination of the weights of the heavy through trains at the heaviest period of the year showed an average of 275 tons behind the locomotive draw-bar per passenger train, and of 410 tons per goods train; the maximum weight of passenger train only slightly exceeded 400 tons and was hauled by two engines. With rare exceptions the heaviest passenger trains do not exceed 350 tons, or goods trains 800 tons, trains of greater weight being almost invariably hauled by two locomotives. The combined maximum tractive effort of two steam locomotives such as are commonly used for these trains would be 16 tons for the passenger train and 21 tons for the freight train, and on occasions the combination might be such as to give 20 and 25 tons respectively. It is evident, therefore, that from a practical standpoint there is no objection to single electric locomotives with initial draw-bar pulls analogous to these combinations.

It is not realized by many engineers and others that the electric locomotive can be applied with both profit and facility to both fast passenger and freight services as well as to suburban work.

The General Electric Company in U.S.A. have recently completed and tested a 107-ton, 1 500-volt, high-speed passenger locomotive of the 2–C–C–2 articulated type for the Paris–Orleans Railway. This machine easily attained its guaranteed speed of 81 m.p.h., and a maximum speed of 105 m.p.h. was sustained during the final runs.

Brown, Boveri are also building for the Paris–Orleans Railway some 2–D–2, 1 500-volt locomotives capable of developing 2 580 h.p. for 1 hour, their weight being 92 tons, maximum speed 81 m.p.h., haulage capacity 600 tons behind the draw-bar up a 1 in 75 gradient at 40 m.p.h.; also a C–C freight locomotive developing 3 600 h.p. for 1 hour, its weight being 114 tons (all adhesive weight), maximum speed 50 m.p.h., haulage capacity about 1 000 tons behind the draw-bar up a 1 in 75 gradient at 25 m.p.h.

In order to consider the comparative costs of fuel and current the following basis has been taken:—Generation, three-phase at 11 000 volts; overhead three-phase transmission at 44 000 to 66 000 volts according to distance; conversion by mercury arc rectifier to 1 500 volts (d.c.), and distribution at this voltage by third rail, with overhead equipment in stations and station yards.

The author has endeavoured to arrive at a generally applicable graph expressing the cost of energy for electric traction as compared with steam, in pence per locomotive-mile, the energy being that required at the tread of the wheels of the tractor for propelling both the tractor and the train hauled by it (Fig. 8).

In the following pages the expression "gross ton-miles" refers to the total weight of tractor, train and train load; and "trailing ton-miles" to the total weight of train and train load behind the tractor.

The cost of coal for locomotive purposes has been assumed to be 23s. per ton delivered to the locomotive depot in wagons, equivalent to 7·40d. per engine-mile at 60 lb. of coal per mile, and the cost of a high-tension unit at the 44 000-volt busbars at the power station to be 0·40d. with coal at 15s. per ton. This figure for the price of locomotive steam coal is a conservative one, as will be realized from Table 4 which shows the price of coal as delivered to the locomotive shed yard for stations at varying distances from London, and also some comparative prices of coal for power-station purposes.

TABLE 4.

Typical Costs of Locomotive Coal delivered in Wagons to Locomotive Running Shed.

Distance from London	Pit price * plus carriage on other railway systems	Distance hauled	Railway carriage on own railway at ½d. per ton-mile	Total cost of coal in wagon at locomotive running shed
miles	s. d.	miles	s. d.	s. d.
299	26 11	81	Nil	26 11
209	20 7	72	3 0	23 7
158	20 8	82	3 5	24 1
157	20 9	25	1 0½	21 9½
82¾	21 3	79	3 3½	24 6½
5	20 9	168	7 0	27 9
Average for coal for main-line services †	21s. 10d.	84½	2s. 11½d.	24s. 9½d

* *The Times Supplement* of 31st January, 1924, states that the average pit-head price in 1922 was 10s. 2¾d., and export coal 25s. per ton f.o.b.
† The average calorific value of the above coals is about 13 500 B.Th.U., with 9 to 10 per cent of ash.

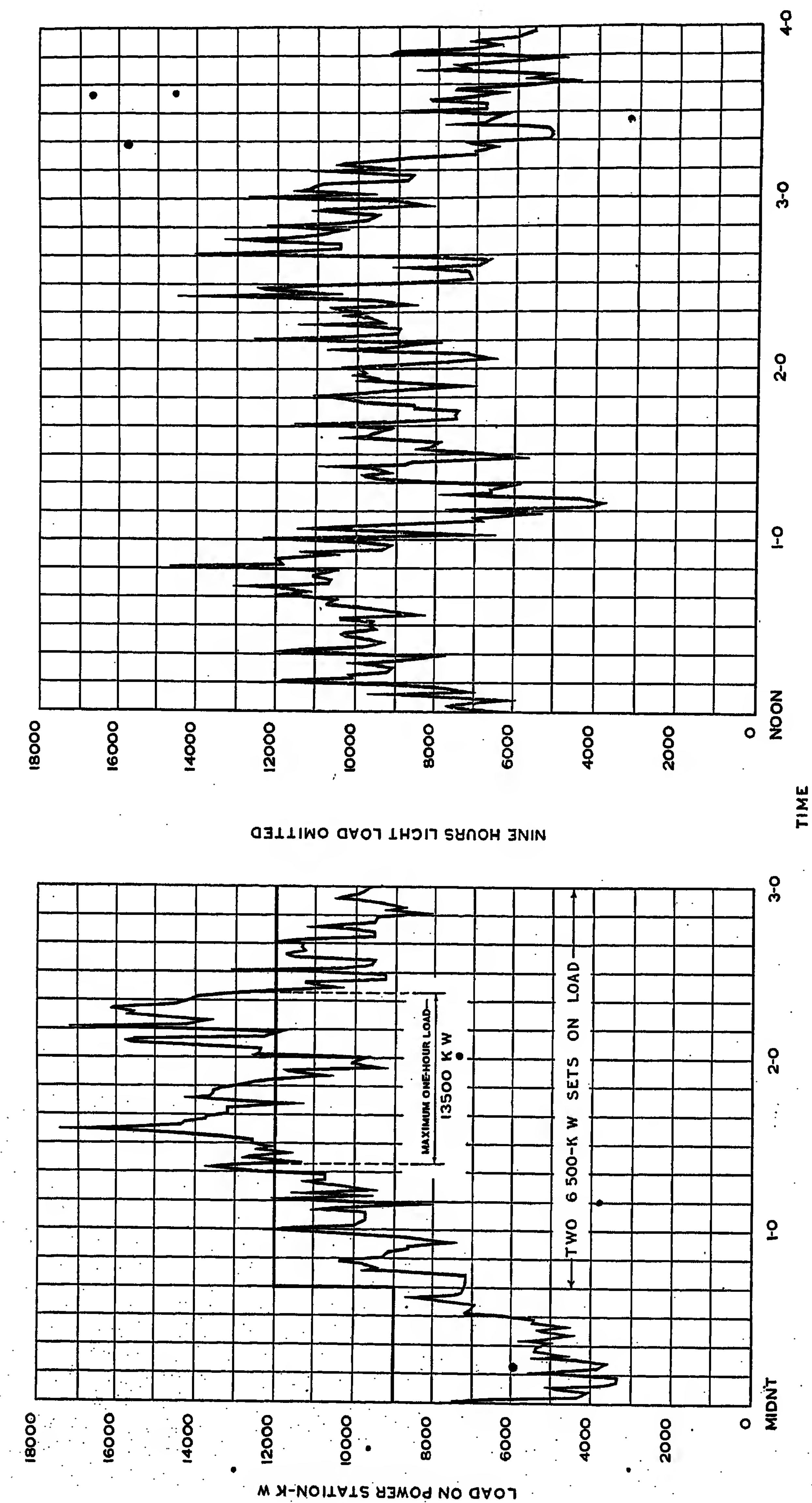

FIG. 6.—Load curve on power station for 100-mile section of main line.

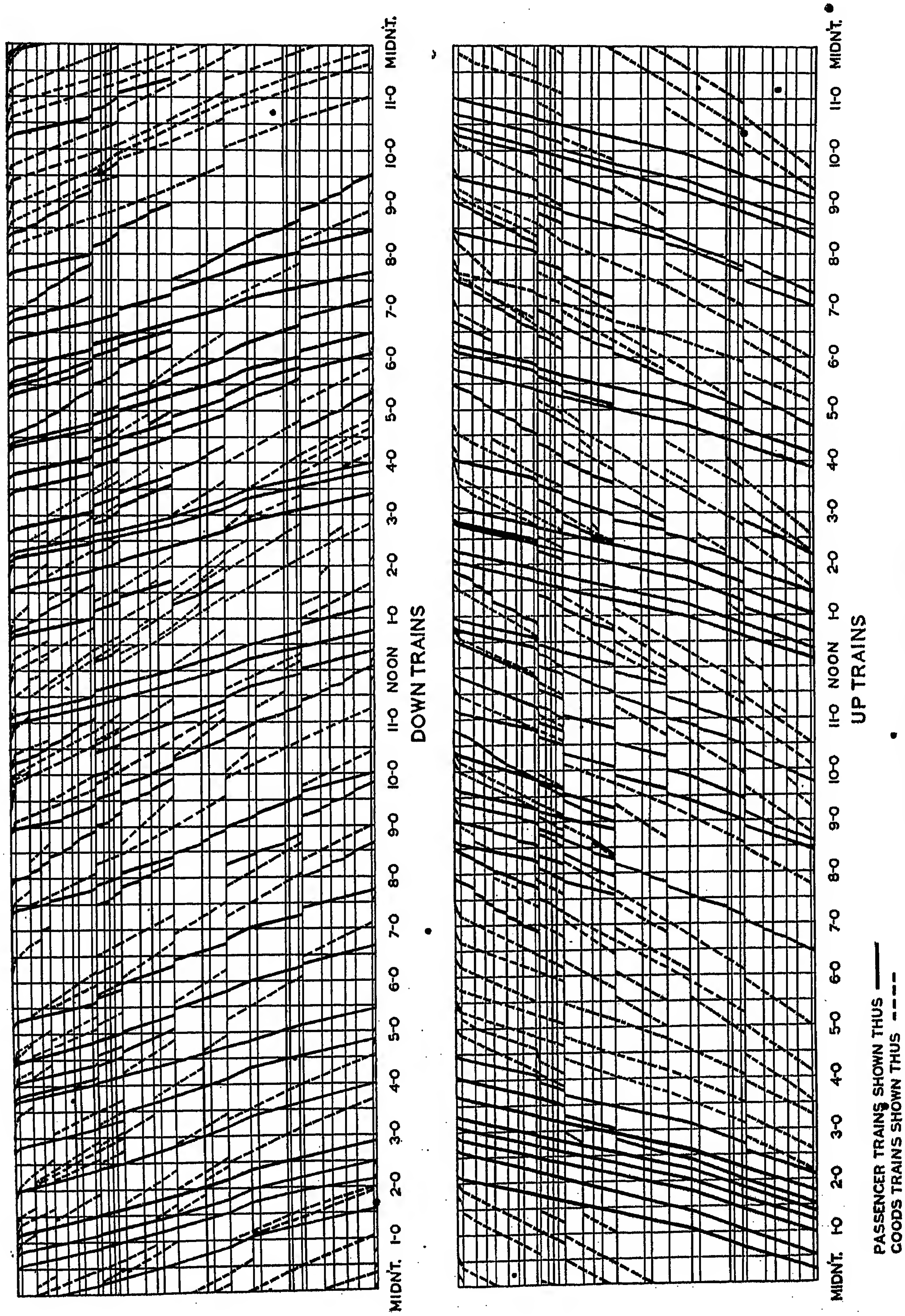

FIG. 7.—Graphical time-table for 100-mile section of main line.

It will be convenient at this point to refer to the load factor which would probably be obtained for such a supply, the load factor being defined as the ratio of the total units delivered to the high-tension feeders per

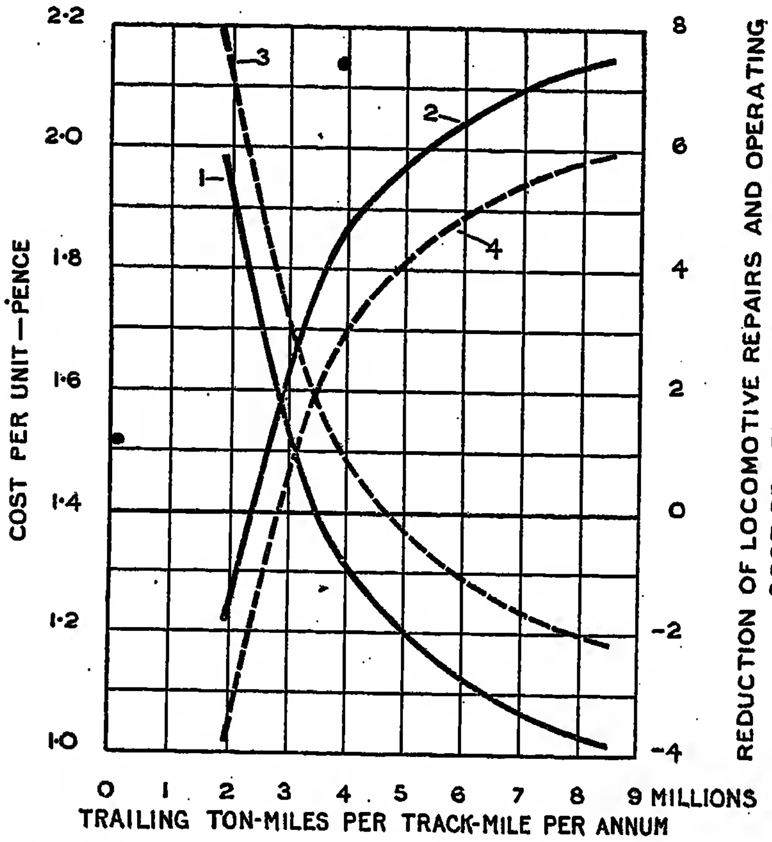

Fig. 8.

Curve 1. Total cost per unit.
Curve 2. Reduction of locomotive repairs and operating cost due to electrification. } From Tables 7 and 8.
Curve 3. Total cost per unit.
Curve 4. Reduction of locomotive repairs and operating cost due to electrification. } Ditto, but with current at 0·5d. per unit instead of 0·4d., and cost of track equipment increased by 10 per cent.

annum to the maximum hourly load multiplied by 8 760 (the number of hours in a year).

The load factor on the suburban electrifications of the L.M. and S. Railway, where there is practically no load from 12 midnight to 6 a.m. and where the load diminishes between 10 a.m. and 4 p.m. to between 66 per cent and 50 per cent of its rush-hour value, is of the order of 40 per cent. In all these cases the load factor is improved by the use of batteries operating in parallel with the converter plants, but tests made with the batteries eliminated show that the resultant load factor is only reduced by about 5 per cent by their absence.

Examination of the actual electrical load to be anticipated on a section of straightforward main-line double track with a density of 5 million trailing ton-miles per track-mile per annum indicates a load factor of about 50 per cent (see Figs. 6 and 7). It may be taken as a postulate that any length of main line worth electrifying will have a load factor of not less than this, and that where goods traffic and, particularly mineral traffic, predominate, the load factor will run up to as high as 70 per cent. These high load factors will naturally result in a low coal consumption and a low cost per unit whether the supply be generated at a railway company's own power station or whether it be purchased.

Table 5 shows in the first four columns some typical costs of generation in economical stations in Great Britain with load factors varying between 25 per cent and 30 per cent. These costs have been brought to a common basis, which assumes a rate of 8 per cent for interest on capital and depreciation combined and is further based on coal at 15s. per ton. It will be seen that the cost of a high-tension unit delivered to the feeders is about 0·46d., the average coal consumption of these stations being about 1·9 lb. per unit. The generating costs of a typical power station producing current for suburban traction, and of an assumed railway generating station working on the load produced by a main-line electrification, are also given on the same basis. From the load factor obtainable from a main-line electrification, and from

Table 5.

Typical Cost per Unit Delivered to H.T. Feeders, British Generating Stations.

Station	A	B	C	D	Typical railway power station supplying suburban electrification	Estimate for main-line generating station
Load factor, per cent	25·3	31·2	25·2	—	40	50
Coal per unit, lb.	1·86	1·95	2·4	1·9	2·4	1·8
Coal at 15s. per ton*	0·1495d.	0·1568d.	0·1929d.	0·1527d.	0·1929d.	0·1447d.
Oil, waste, etc.	0·0035d.	0·0043d.	0·0050d.	0·0050d.	0·0020d.	0·0020d.
Repairs	0·0352d.	0·0345d.	0·0463d.	0·0500d.	0·0350d.	0·0250d.
Salaries and wages	0·0415d.	0·0482d.	0·0557d.	0·0750d.	0·0570d.	0·0450d.
Interest and depreciation, at 8 per cent	0·2132d.	0·1952d.	0·1852d.	0·2000d.	0·1030d.	0·1650d.
Total cost per unit	0·4429d.	0·4390d.	0·4851d.	0·4827d.	0·3899d.	0·3817d.

* Including handling and ash removal.

consideration of these results and those obtained at Blackburn, the probable cost per high-tension unit may be assumed not to exceed 0·40d.

Table 6 shows the average yearly efficiencies of transmission and conversion assumed, and these may be compared with those actually obtained in practice on the suburban electrifications.

The cost per high-tension unit of 0·4d. is increased therefore to 0·6d., on the score of efficiency alone, for the equivalent in energy of 1 000 watt-hours at the tread of the wheels. To obtain the actual cost of this energy the total units used must bear the further cost of operation, maintenance, interest and depreciation of the high-tension and low-tension transmission systems and the converting plant.

It may be assumed without any very great error that the low-tension 1 500-volt distribution system will for any given 100 miles of route remain constant whatever the density of traffic. Considerations of life of equipment and of stability and strength will dictate the use of a fairly large conductor, the substation spacing and size of substation equipment being varied to suit the density of traffic and varying almost directly as that density.

TABLE 6.

Efficiencies of Transmission.

	Average of existing suburban electrification	Author's estimate for a main-line electrification	Mr. Parodi's estimate	Mr. Roger Smith's estimate
	per cent	per cent	per cent	per cent
H.T. transmission	97	94·5	95 *	95
Transformation and conversion	91	92	83	85
L.T. transmission	90	90	95	90
Efficiency from loco shoe to tread of wheel	85	85	85	85
Overall efficiency	67·5	66·5	63·6	60

* Assumed by author.

The cost of the high-tension transmission, if overhead, will also remain approximately constant per mile of route where it is derived from a single generating station supplying a division of main line from 50 to 150 miles in length, the voltage being varied to some extent to suit the load and the distance of transmission.

The watt-hours per ton-mile required for the types and weights of trains hauled on sections of British main line carrying dense traffic are not easily determined, nor are there any general statistics available as to the coal consumption per ton-mile, either gross or trailing, for steam locomotives.

The L.M. and S. Railway have, however, within the last two years carried out a number of dynamometer car tests with main-line trains, the results of which are given in abstract in Table 7. The dynamometer car is fitted with an integrator which records the horse-power-hours at the drawbar, and it is possible from these records, and from the published results of others, to deduce a figure for the watt-hours per trailing ton-mile which would be used by an electrically hauled train, and for the coal per ton-mile which would be used by a steam-hauled train for a general main-line service. It will be observed that the records have been made with very heavy and fast trains on routes with heavy gradients, and with both passenger and goods trains. The results are therefore probably on the high side.

The average figures of the tests are as follows:—

Max. draw-bar h.p. recorded for one locomotive	1 232
Max. speed on the level or on up gradient, m.p.h.	65
Lb. of coal per ton-mile gross, including all losses	0·175
Horse-power-hours per trailing ton-mile ..	0·036
Equivalent watt-hours per trailing ton-mile ..	26·8
Lb. of coal per draw-bar h.p.-hour, excluding shed duties	4·52
Lb. of coal per draw-bar h.p.-hour, including shed duties	5·89

In regard to the figure of 26·8 watt-hours per ton-mile, if the gross weight of train be taken at 320 tons, Mr. Roger Smith uses the figure of 26 and Mr. Parodi estimates it at about 30.

Figures taken from tests on other routes in Great Britain, given in Mr. Hughes's paper before the Institution of Mechanical Engineers on superheating and compounding, tend to show, allowing for the fact that all the figures examined are test-results made presumably with engines in first-class condition with picked drivers, that the figure of 0·175 lb. of coal per ton-mile used as the basis of calculating gross train weight is probably a fair approximation to the truth.

A rough check on the accuracy of these figures is given by multiplying the coal per ton-mile thus experimentally obtained by the estimated gross ton-miles for a 100-mile section of main line carrying traffic very similar to that of the tests. The annual coal consumption thus obtained only differed by 1·6 per cent from the actual coal consumption for the year 1922.

Except as regards suburban electrified lines, gross ton-mile figures do not exist: the only figures available in the Ministry of Transport statistics, or easily obtainable from the railway companies' own records, are engine-miles divided under various heads such as passenger, freight, shunting, light, average freight train load, coal per engine-mile for passenger, freight and shunting services, and the number of wagons per freight train.

To obtain a fairly reliable estimate of the ton-miles per annum for any railway system it is first necessary to obtain figures for the average weight of each class of train.

From the coal per engine-mile and the coal per gross ton-mile as ascertained by test, it is possible to estimate the gross weight of each class of train. An arbitrary estimate of the weight of locomotive enables a deduction to be made for this, leaving the trailing weight of each class of train.

In the case of freight trains the average trailing load thus obtained may be checked by taking from

TABLE 7.

Comparative Statement of Efficiencies of Steam Locomotives on a British Railway as Derived from Dynamometer Car Tests and Calculated Efficiencies of Electric Locomotives doing Similar Work at Similar Speeds.

Averages of	Speed		Steam Locomotive								116-ton Electric Locomotive				
	Over whole run	Doing positive work	Coal consumed, including shed duties per		Total watt-hours per gross ton-mile	Draw-bar watt-hours per trailing ton-mile	Thermal efficiency of locomotive with coal of 13 481 B.Th.U.'s per lb.				Coal consumed at power station per		Total watt-hours per gross electric ton-mile	Thermal efficiency of locomotive with coal of 11 000 B.Th.U.'s per lb. and overall electrical efficiency from power station to tread of driving wheel = 66·6 per cent. Coal consumption at power station per unit = 1·98 lb.	
							Gross h.p.-hours		Draw-bar h.p.-hours						
			Gross ton-mile	Trailing ton-mile			Excluding shed duties	Including shed duties	Excluding shed duties	Including shed duties	Gross ton-mile	Trailing ton-mile		Gross h.p.-hours	Draw-bar h.p.-hours
Main-Line Passenger Runs: 48·8 Miles. Passenger runs: 8 outward .. Passenger runs: 8 inward ..	m.p.h. 39·19 39·20	m.p.h. 38·49 38·65	lb. 0·1912 0·1637	lb. 0·2399 0·2054	Wh 31·65 30·28	Wh 27·53 26·01	per cent 5·397 6·367	per cent 4·212 4·713	per cent 3·733 4·352	per cent 2·916 3·226	lb. 0·0829 0·0782	lb. 0·1033 0·0987	Wh 27·90 26·18	per cent 10·44 10·44	per cent 8·19 8·19
Average of outward and inward runs	39·20	38·57	0·1775	0·2226	30·96	26·77	5·882	4·463	4·043	3·071	0·0805	0·1013	27·04	10·44	8·19
Goods runs 5 (special and only one way) 24·5 miles	16·09	16·22	0·1682	0·1858	23·79	22·75	5·190	3·593	4·509	3·122	0·0667	0·0737	22·44	10·44	9·54
Mean of 16 passenger and 5 goods runs			0·175												
Main-Line Passenger Run: 141 Miles. Single-headed in steam case: Outward .. .. Inward	50·85 48·50	49·50 48·60	0·1482 0·1367	0·1929 0·1808	32·00 31·75	25·88 25·27	6·110 6·675	5·470 5·880	3·793 4·017	3·396 3·537	0·0780 0·0768	0·1004 0·1005	26·24 25·80	10·44 10·44	7·98 7·81
Average of outward and inward runs..	49·67	49·05	0·1425	0·1868	31·88	25·58	6·393	5·675	3·905	3·466	0·0774	0·1005	26·02	10·44	7·89
Main-Line Passenger Run: 90·1 Miles. Double-headed in steam case only: Outward .. .. Inward	54·07 50·55	54·00 50·50	0·1718 0·1554	0·2553 0·2307	42·00 39·10	32·33 30·10	7·540 7·930	6·190 6·360	3·902 4·110	3·203 3·300	0·0973 0·0906	0·1198 0·1116	32·72 30·50	10·44 10·44	8·37 8·35
Average of outward and inward runs..	52·31	52·25	0·1636	0·2430	40·55	31·21	7·735	6·275	4·006	3·251	0·0939	0·1157	31·61	10·44	8·36
Main-Line Goods Run: 90 Miles. Double-headed in steam case only: Outward .. .. Inward	38·52 41·40	39·00 41·00	0·1358 0·1616	0·1369 0·1680	40·07 48·20	36·75 32·80	9·065 9·530	7·465 7·540	6·045 6·240	4·978 4·940	0·1053 0·0933	0·1245 0·1112	35·37 31·45	10·44 10·44	9·18 9·15
Average of outward and inward runs..	39·96	40·00	0·1487	0·1775	44·14	34·78	9·298	7·503	6·143	4·959	0·0998	0·1178	33·41	10·44	9·16
Mean of all runs						20·80									

NOTE.—For detailed explanation of basis of figures in above table see Appendix 4.

the statistics the number of wagons per freight train and the average net tons of load per train; by assuming an average tare weight for the wagons the trailing tons weight of freight train may thus be ascertained. The figures obtained by these two different methods may be further examined in the light of the actual average weights of both passenger and freight trains taken over 2 days at a period of the year when traffic is fairly heavy on a 100-mile double-track section of main line carrying mainly through traffic, and with an average weight of train for the same section obtained in a different way. Details of the methods of arriving at these figures are shown in Table 8. These figures show a fair measure of agreement and are sufficient to demonstrate that the assumption, for the purpose of calculating ton-miles per mile of single track of an average trailing train weight for all classes of traffic of 250 tons, is fairly correct and, if anything, gives the advantage to the steam locomotive when the figure is used as a basis for traffic density and the units per engine-mile.

Table 9 shows how, on the basis of the cost of electrification of 100 miles of double track, the cost of the equivalent of 1 000 watt-hours at the tread of the electric locomotive wheels in relation to the density of traffic in trailing ton-miles per mile of track per annum is built up. From the assumption that the gross train weight, i.e. that of the locomotive plus the trailing load, is 320 tons, the units required per engine-mile and the cost of current per engine-mile are deduced; it will be noted that this cost of current includes all fixed charges. It appears that the cost of current will always be higher per engine-mile than that of coal per engine-mile delivered to the locomotive running shed, but that at any density of traffic equal to or higher than 2 300 000 trailing ton-miles per track-mile per annum, the lower costs of operation of the electric tractor more than compensate for this increase in the cost of energy.

Table 10 shows the application of this current cost to the whole cost of locomotive operation and the consequent reduction which may be expected in the total cost of locomotive operation per engine-mile in relation to the density of traffic.

Fig. 8 shows in graph form the cost per unit at the locomotive wheel and the reduction of cost per engine-mile due to electrification. It also shows the corresponding costs if the cost of current is taken at 0·5d. per unit instead of 0·4d. and the cost of track equipment increased by 10 per cent. The figures have been taken on a very conservative basis so that it may be assumed that, even discounting to some extent the reduction in operating costs, main-line electrification is worth carrying out at a density of 3 000 000 or more trailing ton-miles per track-mile per annum.

It will be noticed that no addition has been made to the cost per engine-mile for electric working to cover any capital charges on the new locomotives that would have to be provided to replace steam locomotives. This charge does not arise, because the whole cost will be borne by the Renewal Fund. The ratio of the cost of the electric locomotive to the cost of the steam locomotive for equal draw-bar pull and draw-bar horse-power is less than 1·7 : 1 on the average, but, as the

TABLE 8.

Weights of Trains on Various British Railways as Derived from Ministry of Transport Statistics, and Coal per Ton-Mile as Experimentally Determined.

Railway	Freight Trains								Passenger Trains				Shunting			
	Average train load * (a)	Average number of wagons per train *	Average weight of train wagons, assuming tare weight of wagons at 5 tons (b)	Coal per engine-mile *	Gross weight of train, deduced from 0·175 lb. of coal per ton-mile (c)	Assumed average weight of engine (d)	Average trailing weight of train (a + b)	Average trailing weight of train (c − d)	Coal per engine-mile *	Gross weight of train deduced from 0·175 lb. of coal per ton-mile	Assumed average weight of engine	Average trailing weight of train	Coal per engine-mile *	Gross weight of train, deduced from 0·3 lb. of coal per ton-mile	Assumed average weight of engine	Average trailing weight of train
	tons		tons	lb.	tons	tons	tons	tons	lb.	tons	tons	tons	lb.	tons	tons	tons
A	126·8	36·5	182·5	71·44	407	90	309	317	51·63	295	90	205	44·3	148	50	98
B	136	35·9	179·5	58·35	334	90	310	244	47·14	270	90	180	46·25	154	50	104
C	142·2	39·9	199·5	78·06	446	90	342	356	53·61	306	90	216	50·34	168	50	118
D	110	35·4	177·0	44·94	257	90	287	167	39·0	223	90	133	31·7	106	50	56
E	101	31·25	156·25	56·6	323	90	257	233	50·14	286	90	196	38·26	127	50	77
F	104·9	33·20	166·0	53·32	307	90	271	217	41·88	239	90	149	43·69	146	50	96
G †	—	41·5	—	—	510	100	—	410	—	385	110	275	—	—	—	—

* Derived from Ministry of Transport statistics.

† Represents actual average weights of passenger and goods trains taken over two days on a double-track section of main line 90 miles long.

TABLE 9.

Relation of Cost of Current per Engine-Mile to Traffic Density per Track-Mile.

Traffic density in trailing ton-miles per track-mile, excluding sidings	Density: engine-miles per track-mile per annum	Gross ton-miles per 100 route miles of double track. (Ratio of gross ton-miles to trailing ton-miles $=\frac{320}{250}=1\cdot28$)	Number of units per 100 route-miles at locomotive wheel tread, based on 30 watt-hours per gross ton-mile	Cost of high-tension transmission lines and step-up transformers for 200 track-miles	Cost of sub-stations for 200 track-miles	Cost of track equipment, including special work for junctions and sidings for 200 track-miles	Total cost (A)	Interest at 5 per cent per annum	Depreciation on 5 per cent sinking fund basis (25 years) $=(A)\times0\cdot021$	Sub-station wages and maintenance	H.T. transmission maintenance at £20 per mile and 1 per cent per annum for step-up transformers	Track equipment maintenance at £50 per mile of track plus additional cost of maintenance of track at £20 per track-mile per annum	Total fixed charges: interest, depreciation, operation and maintenance	Fixed charges per l.t. unit at locomotive wheel tread	Cost of l.t. unit without fixed charges, allowing for efficiency of transmission, conversion, and electrical and mechanical efficiency of locomotive	Total cost per l.t. equivalent unit at locomotive wheel	Cost of current per engine-mile
ton-miles 2 000 000	8 000	ton-miles 512 000 000	kWh 15 360 000	£ 197 000	£ 204 000	£ 500 000	£ 901 000	£ 45 050	£ 18 920	£ 6 000	£ 1 770	£ 14 000	£ 85 740	d. 1·34	d. 0·6	d. 1·94	d. 18·6
3 000 000	12 000	768 000 000	23 040 000	201 000	263 000	500 000	964 000	48 200	20 245	6 000	1 840	14 000	90 285	0·940	0·6	1·540	14·8
4 000 000	16 000	1 024 000 000	30 720 000	215 000	263 000	500 000	978 000	48 900	20 540	6 000	1 920	14 000	91 360	0·713	0·6	1·313	12·6
5 000 000	20 000	1 280 000 000	38 400 000	223 000	322 000	500 000	1 045 000	52 250	21 945	7 000	2 000	14 000	97 195	0·607	0·6	1·207	11·6
6 000 000	24 000	1 536 000 000	46 080 000	227 000	360 000	500 000	1 087 000	54 350	22 830	8 000	2 080	14 000	101 260	0·528	0·6	1·13	10·85
7 000 000	28 000	1 792 000 000	56 760 000	245 000	392 000	500 000	1 137 000	56 850	23 880	9 000	2 160	14 000	105 890	0·473	0·6	1·073	10·32
8 000 000	32 000	2 048 000 000	61 440 000	249 000	454 000	500 000	1 203 000	60 150	25 260	10 000	2 230	14 000	111 640	0·436	0·6	1·036	9·95

Units per engine-mile are based on 250 trailing and 320 gross ton-miles per engine-mile. This low figure is due to the inclusion of shunting-miles in engine-miles. Units per engine-mile = 320 ton-miles × 30 watt-hours per ton-mile = 9·6.

Transmission costs are based on overhead conductor, in duplicate, varying in size from 0·05 sq. in. to 0·1 sq. in. Pole line exclusive of copper, taken at £2 000 per mile. H.T. circuit 80 miles at 44 000 volts, 3 phase. Step-up transformers are based on the maximum hourly load of power station in each case with 50 per cent load factor: 4 in service and 2 stand-by taken at £1 per kW.

Substation costs based on £12 per kW installed.

Substation wages based on partial automatic operation.

Track cost based on £2 000 per mile and 10 per cent for special work and 60 miles of sidings (23 per cent of total track-miles).

Cost of track equipment for sidings taken at half main-line cost.

Ten per cent added for special work at junctions on main line.

TABLE 10.

Reduction in Operating Cost per Engine-Mile, due to Electrification, for Various Traffic Densities.

Traffic density: Trailing ton-miles per track-mile	Traffic density in engine-miles per track-mile. [Trailing ton-train-miles ÷ average trailing weight of train (250 tons)]	Cost of electric locomotive operation per engine-mile	Cost of current per engine-mile	Total cost of electric locomotive operation per engine-mile	Cost of steam locomotive operation per engine-mile*	Economy per engine-mile
		d.	d.	d.	d.	d.
2 000 000	8 000	8·90	18·6	27·5	26·24	1·26 loss
3 000 000	12 000	8·90	14·8	23·7	26·24	2·54
4 000 000	16 000	8·90	12·6	21·5	26·24	4·74
5 000 000	20 000	8·90	11·6	20·5	26·24	5·74
6 000 000	24 000	8·90	10·85	19·75	26·24	6·49
7 000 000	28 000	8·90	10·32	19·22	26·24	7·02
8 000 000	32 000	8·90	9·95	18·85	26·24	7·39

* Coal 7·40d. per engine-mile, based on 60 lb. per engine-mile at 23s. per ton; other charges per engine-mile = 18·84d. (see Table 3). Total = 26·24d.

TABLE 11.

Density of Traffic on Various British Railways and Sections of these Railways, as Derived from the Ministry of Transport Statistics.

Railway	Miles of single track			Percentage of sidings to total mileage	Total steam engine-miles, including shunting	Total steam engine-miles, excluding shunting	Engine-miles per track-mile, including shunting and excluding sidings, per annum	Engine-miles per track-mile, excluding shunting and excluding sidings, per annum	Coal per gross ton-mile, dynamometer car figure	Coal per engine-mile for all services	Gross weight of train	Assumed weight of engine	Trailing weight of train	Density of traffic: trailing ton-miles per track-mile	
	Excluding sidings (X)	Sidings only	Total		(Y)	(Y')	$\left(\frac{Y}{X}\right)$	$\left(\frac{Y'}{X}\right)$					(Z)	Including shunting $\left(\frac{Y}{X}\times Z\right)$	Excluding shunting $\left(\frac{Y'}{X}\times Z\right)$
	miles	miles	miles	per cent					lb.	lb.	tons	tons	tons	ton-miles	ton-miles
A	5 738	2 358	8 096	29	96 791 748	61 535 618	16 870	10 750	0·175	58·84	336	90	246	4 150 000	2 640 000
B	3 569	1 831	5 400	33·9	64 344 572	42 566 799	18 000	11 950	0·175	52·89	302	90	212	3 820 000	2 540 000
C	1 981	900	2 881	31·3	25 292 037	17 548 228	12 750	8 850	0·175	64·21	367	90	277	3 530 000	2 450 000
D	1 700	456	2 156	21·2	21 240 245	15 262 542	12 500	8 950	0·175	39·81	228	90	138	1 734 000	1 235 000
E	1 291	348	1 639	21·3	18 741 835	13 525 692	14 500	10 450	0·175	49·98	286	90	196	2 840 000	2 050 000
F	901	354	1 255	28·2	13 812 566	10 887 363	15 300	12 050	0·175	44·69	255	90	165	2 525 000	1 990 000
G	200	—	—	—	4 000 000	—	20 000	—	0·175	60	343	90	253	5 060 000	—
H	2 223	732	2 955	24·8	36 000 000	28 840 000	16 200	12 970	0·175	60	343	90	253	4 100 000	3 280 000
J (electric)	112	9	121	7·4	2 360 332	2 204 113	21 000	20 200	0·371	57·7	155	49	106	2 225 000	2 140 000
K (electric)	166	15	181	8·3	3 780 864	3 775 735	22 900	22 880	—	—	—	—	—	—	—
L (electric)	63	7	70	10·0	1 266 276	1 252 075	20 100	19 900	—	—	—	—	—	—	—

annual mileage per electric locomotive will be double or more than double that of the steam locomotive, the total cost of the new electric rolling stock will not be as great as that of the steam locomotives which are replaced. For particulars as to relative cost reference should be made to Appendix 2.

The application of these figures of traffic density with the consequent costs to the actual traffic densities of British railways is a matter of some difficulty. To assist in giving a correct picture of traffic densities, Table 11 has been prepared. This shows the traffic densities on some of the principal former railway systems in engine-miles per mile of single track, exclusive of sidings; the same for certain electrified lines; the coal per engine-mile; the average weight of train based on coal per engine-mile and the experimental figure of 0·175 lb. of coal per gross ton-mile; and the consequent density of traffic in trailing ton-miles per track-mile per annum. More detailed figures for one of the systems referred to are also given in Appendix 3.

It will be seen that, taken as a whole, most of the systems fall within the category of possible successful main-line electrifications.

As each of these large systems includes many branch lines with very sparse traffic which could not be profitably electrified, it follows that the main traffic routes must have much higher traffic densities and that electrification on the score of reduced costs for locomotive maintenance and operation alone will be remunerative.

The figures given in the paper indicate that main-line electrification is a probable source of largely increased revenue, and that a thorough investigation of the possibilities of electrification in connection with the main arteries of railway traffic is very desirable.

The author has confined himself strictly to the economies obtainable under Abstracts B and C of the railway accounts, omitting the cost of engine renewals which is assumed to be the same.

It is not within the ambit of a railway electrical engineer to discuss the possible traffic economies which may accrue due to main-line electrification, or the possibilities of accelerated schedules and the consequent growth of traffic, but a substantial increment to the increased net profits indicated is undoubtedly obtainable from traffic sources.

It is necessary also to emphasize the fact (already taken into account by the French Government and railway managements) that an extensive electrification brings a cheap and abundant supply of electricity to large areas of the country now devoid of such supplies.

Assuming that after full investigation of the operating conditions on a considerable section of main line comprising, say, 1 500 miles of track, it was found that the author's broad conclusions were fully justified so that the method of electrification became an immediate problem, there would be several difficult points to consider.

Such an electrification covering possibly 500 miles of route would not be supplied by a single generating station, but would usually be supplied from at least six, and probably from eight, generating stations; consequently the length of high-tension transmission lines would not bear as large a ratio to the route mileage as has been used in Table 9. The use of cables would raise the price of current to a prohibitive figure, and therefore overhead transmission is practically compulsory. Such transmissions, however, are not desirable on the railway itself, not only on account of difficulties in finding a route for the transmission line but also on account of the undoubted interference troubles which would arise in connection with telegraph, telephone and signal circuits. The power company or municipal stations giving the supplies will therefore be obliged to construct overhead transmission lines to the points chosen by the railway company for their substations. The existing electricity supply areas are such as to make it probable that a number of Special Orders would be required, and it would seem that some legislation is desirable which would facilitate the construction of such transmission lines for railway-supply purposes.

The track equipment will in the main be on the third-rail system, but considerations of continuity of contact at junctions, particularly with reference to freight locomotive operation, will necessitate short lengths of overhead distribution, thus involving the provision of both collector shoes and bows on the locomotives. As the overhead collector must be clear above the structure gauge, the bow in its "up" position fouls the structure gauge, and means will therefore have to be provided whereby the bow automatically rises to meet any stretch of overhead trolley and automatically falls when it leaves it, or, alternatively, every overbridge and tunnel will have to be equipped with a dummy trolley. Unless means are provided for making the bow dead when the third-rail shoes are alive, these dummy sections will have to be insulated for the full line pressure.

The cost of electrification of sidings is of importance. It will be observed from column 5 of Table 11 that the mileage of sidings on a railway system with heavy traffic represents from 20 to 30 per cent of the total track mileage. In addition to these railway-owned sidings there is a large mileage of privately owned sidings over which railway companies' locomotives work. It has not yet been possible to determine whether sidings would be more economically dealt with by electrification with overhead conductors or by operation with storage-battery locomotives. Probably both methods would be adopted. In some cases the cost of the overhead work for the sidings would be nearly as high as for the main track. The work carried out at Melbourne in connection with Flinders-street and that done on the Newport–Shildon line, however, give grounds for assuming that it is probable that as a whole the cost per mile of electrification of the sidings would not exceed half that of the main tracks.

The provision of electric locomotives capable of the maximum utilization of traffic, which is of the utmost importance in view of their capacity for continuous traffic, is perhaps the most difficult problem of all. Its solution is, however, facilitated by the approximation of the speed of freight and passenger trains made possible by electric traction.

The advantage of the increased speed possible with

freight trains hauled by electric locomotives was very clearly brought out by Mr. Watson in the discussion on Sir Philip Dawson's paper on "The Financial Prospects of Railway Electrification" read before the Institute of Transport on 7th May, 1923. Mr. Watson stated that there were two speeds of passenger trains between New York and Newcastle, and five speeds for freight trains; in consequence, there was a large waste of engine time by trains of lower priority having to give preference to those of higher priority. Electrification was going to reduce these seven speeds to three: 90 per cent of the train mileage would be run at two speeds only, namely, 60 m.p.h. for fast expresses and 30 m.p.h. for stopping passenger trains and freight trains.

The speed of freight trains is in general limited by (1) the brake power available, and (2) the efficiency of axle-box lubrication. In regard to the latter, the existence of a very large number of grease-lubricated axle boxes is the limiting feature. Maximum speeds of 45 m.p.h. are, however, usual even with these grease boxes, and the average speed can obviously be raised very considerably. The electric locomotive can be braked in new designs to a greater extent than the average of the steam freight locomotives now in use. The utilization of field control also permits of a very wide range of speed with a comparatively small percentage of weight variation in the motors.

Standardization of design and the use of a minimum number of types will therefore be essential conditions of success. From the experience gained in France and elsewhere it would seem that three types should suffice for the new conditions which will be brought about by electrification: (1) B–B type for shunting and local freight services; (2) B–B type for ordinary freight; (3) 2–D–2 type for fast freight and express passenger work. The whole locomotive design can be common for the first two types, with the exception of motor, pinion and gear case.

The 2–D–2 type will be utilized when required on full field in the series-parallel motor combination for the services performed by the two B–B types. All types will have four-motor equipments, field control and rheostatic brakes. The determination of the proportionate number of each type to be built will, however, be a matter of extreme difficulty and will finally be decided on an empirical basis. The control of the 2–D–2 type will be used on all types and will be operable in combination with the control used on the multiple-unit trains.

To improve brake control on routes with heavy gradients, electrification makes it possible to equip a certain number of freight brake-vans with collecting shoes, vacuum reservoir, and vacuum pump and vacuum brake gear, thus giving, in case of a break-loose on a rising grade, the goods guard a control over the train much superior to that possible under steam conditions.

The problem of dealing with train-heating is not easy, but the electrically heated boiler used by Sir Vincent Raven on his electric express passenger locomotive will probably have to be used in the initial stages. As electrification progresses trains which circulate exclusively in the electrified area will be fitted with electric heaters, but the present system of lighting will continue. Incidentally, the substitution of electric heaters for the present steam system will eventually effect a substantial economy as compared with the present steam-heating system.

Most difficult of all of solution is the problem of making the main-line express or freight locomotive perfectly safe to operate with one man. This will be a matter for future consideration and, obviously, at the outset of the electrification locomotives handling heavy trains or trains running long distances without a stop will be operated by two men as at present. It may be mentioned that locomotives under 1 000 h.p. are to-day operated by one man on the Loetschberg Railway.

It is evident that such far-reaching changes in the equipment of British railway systems will of necessity bring with them many radical alterations in methods of operation. If the fullest advantage is to be taken of the capabilities of the new system of traction, operating officers will have to adjust their methods to these new conditions.

In conclusion, it will be realized that those in whose hands rests the operation and financial success of a public utility corporation such as a railway naturally shrink from the vast responsibility of expending many millions on the trial of a system of traction so novel and unfamiliar to them, and very rightly are unwilling to embark on such an enterprise without the certain prospect of success. The evidence of certain success has not as yet been put before them, and all the author can hope is to have made a prima facie case for full investigation.

The author wishes to acknowledge the assistance he has received from the writings of many other workers in the field of electric traction, particularly the papers of Sir Vincent Raven, Mr. Roger Smith, Mr. Parodi and Mr. Bachellery.

Summarized Conclusions.

(1) The density of traffic on most of the suburban electrified lines in Great Britain at the present is about 20 000 train-miles per track-mile (excluding sidings) per annum.

(2) The cost of locomotive operation as detailed under Abstracts B and C of the Railway Accounts, excluding locomotive renewals, is less per train-mile for the electric suburban services than per engine-mile for the average of all the steam-hauled services on the larger of the former British railway systems, including all branch lines.

(3) The density of traffic on these systems, including all their branches, in engine-miles per annum approaches the density in train-miles per track-mile, excluding sidings, per annum on the suburban electrified lines, but in ton-miles is greater owing to the greater average weight of train.

(4) As a considerable proportion of the total track mileage is made up of branches with sparse traffic, the density of traffic on the main trunk routes in ton-miles per track-mile per annum must be very much greater than on the electrified suburban lines.

(5) Owing to the standing charges on the capital

expenditure on high-tension transmission lines, sub-stations and track equipment, and the losses in transmission and conversion, current, even if purchased at the generating station busbars at 0·4d. per unit, is more costly than coal as supplied to the tenders of the steam locomotive at the locomotive running sheds.

(6) The cost of current, converted to tractive effort at the electric locomotive wheel-tread, being greater per electric engine-mile than the cost of coal per engine-mile for the steam locomotive, the extent to which this cost is greater depends on:—

(*a*) the density of traffic in ton-miles per running track-mile per annum,
(*b*) the ratio of the siding mileage to the running track mileage,
(*c*) the number of junctions.

(7) The electric locomotive as a tractor compared with the steam locomotive is superior in every way except mobility as a self-contained unit.

(8) In considering operating costs, the total of enginemen's wages will be less due to:—

(*a*) elimination of engine duties,
(*b*) elimination of double crews for double heading,
(*c*) elimination of movements for turning, coaling and watering,
(*d*) utilization of one man instead of two on local trains composed of multiple-unit stock, and on shunting engines.

(9) Shed wages, other than repair wages, will be almost eliminated, as the locomotives will no longer go to the sheds except for repairs and for a fortnightly inspection.

(10) Repairs both at the sheds and at the main repair works are reduced to about one-third of the present cost per engine-mile, due to the elimination of reciprocating parts and the boiler.

(11) The capacity of the existing locomotive repair works and locomotive running sheds is therefore increased.

(12) Water is no longer required, and the cost of it therefore disappears.

(13) Simplification of design of electric locomotives has so lowered their prime cost that the replacement of the steam locomotive by the electric locomotive is a revenue charge.

(14) The capabilities of the electric locomotive for maintaining its normal speed on gradients and in unfavourable weather will permit of a substantial reduction in timings without increase in the maximum speed and with a small increase, of the order of 5 to 10 per cent, in the cost of energy only.

(15) The number of large generating stations in this country is now such as to permit in most cases current to be purchased by the railway companies, and offers the further advantage that an extensive electrification will not be dependent on a single generating station.

(16) The load factor of these purchased supplies should be such as to make the price of current very low.

(17) The figures given in the paper indicate that after paying all fixed charges on capital expended, the railway companies should obtain a further net profit representing from 5 to 10 per cent on the capital expended in electrification.

(18) Apart from the question of development of traffic due to increased facilities, main-line electrification is likely to be more profitable to the railway companies than suburban electrification.

(19) In the paper, only the net profit arising from more economical working of locomotives has been taken into consideration; there will be additional profits arising from:—

(*a*) elimination of necessity for bridge renewals for heavier axle loads,
(*b*) slight reduction of wagon stock due to quicker wagon movement and elimination of locomotive coal traffic,
(*c*) reduction in painting and longer life of bridges and stations,
(*d*) reduced wear and tear of permanent way,
(*e*) reduced wages of goods guards due to reduction in goods train-hours by quicker movement,
(*f*) elimination of necessity for expenditure on loops and widenings,
(*g*) increase in the capacity of the line.

APPENDIX 1.

Data on Reduction in Number of Locomotives by Substitution of Electric Traction, and Reduced Cost of Repairs.

On the New York, New Haven and Hartford Railway, which has 550 miles of electrified track, in 1921 the electric passenger locomotives averaged 33 000 miles per locomotive failure, the average detention per failure being 18 minutes. The annual mileage per locomotive was nearly 60 000. The freight locomotive mileage per locomotive failure was approximately 22 500. These locomotives frequently made two round trips in 24 hours, mileage 272, whereas under steam operation the daily locomotive mileage was from 100 to 120. During the years 1915–1921, 16 electric switching locomotives were in actual service over 70 per cent of the total time, and during 1916 they realized over 77 per cent. These locomotives are operated 24 hours per day, and consistently make 140 miles on the basis of a running speed of 6 miles per hour. They have replaced steam locomotives in the ratio of 1 to 2 and have realized a coal saving of 65 per cent. On the Pennsylvania electrified lines in New York, main-line electric locomotives realized 78 600 miles per detention on account of locomotive troubles, and during one year there was a total train delay of only 55 minutes due to failure of motive power. These locomotives are now averaging about 4 500 miles per month. On the Norfolk and Western Railway two 300-ton electric locomotives now haul trains of 3 250 tons at 14 miles per hour, whereas previously three Mallet steam locomotives were required,

the speed then being 7 miles per hour. Twelve electric locomotives were purchased to replace 24 Mallet engines and still handle the service, although when placed in traffic 33 Mallet locomotives would have been required, and the volume of traffic has also further increased. During 1922 these engines made an average mileage of 37 820, more than 100 miles per day per engine. On the New York, Westchester and Boston Railway during the heavy snowstorms of 1919–1920, when the service on many steam roads was seriously disorganized, operation of the suburban service was 100 per cent perfect. In 1919, the average mileage per car was over 42 000, and the average car-mileage per minute of delay 2 700. On the Philadelphia suburban service of the Pennsylvania Railway approximately 600 trains per day are now operated, as compared with 160 under steam conditions. During the year 1919 over 2 883 000 car-miles were run, with an average of over 48 000 car-miles per detention. Figures taken from the Interstate Commerce Commission Accounts for 1919 give a comparison, brought down to a common basis of 100 tons on the driving wheels, of repairs per locomotive-mile for steam locomotives and direct-current electric locomotives. The cost of repairs and engine-house expenses for steam are 49·8 cents per locomotive-mile, as compared with 9·77 cents per locomotive-mile for the electric, or approximately 2s. per mile for steam as compared with 5d. for electric. If the actual figures per locomotive-mile are taken without considering the weight on the drivers, the cost for steam is about 1s. 8d., as against 6d. for the electric. As further evidence of the extremely low cost of repairs to be anticipated with electric locomotives, the 2–C–1 outside-gear alternating-current electric locomotive of the Swiss Federal Railways was examined after 80 000 miles running, and no wear could be found on the gears nor were any adjustments or repairs required to either motors or gears. This of course is a result unattainable with a steam locomotive, which would have required a heavy general repair after running this mileage from new. From the standpoint of the electrification of British main lines, however, the most important evidence on this crucial question of the cost of repairs comes from Sir Vincent Raven in his paper on electric locomotives read before the Institution of Mechanical Engineers in November 1922.

The North Eastern Railway alone in this country, with the exception of the Metropolitan Railway, has had experience of the actual cost of repairs for locomotives working main-line traffic. On the Newport–Shildon line the 5 electric locomotives which replaced 13 steam had a mileage of over 60 000 miles per annum, and the cost of repairs and shed wages was less than one-seventh of that of steam locomotives doing similar work. In fact these electric locomotives were at least 50 per cent more powerful than steam locomotives of similar weight. The shunting locomotives which have been in use on the same railway for 18 years corroborate these figures, the cost of repairs and shed wages being only one-sixth of that of steam locomotives doing the same class of work.

The Metropolitan Railway operates a number of trains hauled by electric locomotives of the B–B type between Baker-street and Harrow, and the cost of maintaining these is fairly comparable with that of maintaining the steam locomotives which haul the same trains from Harrow onwards. In this case, in spite of some abnormal expenditure on the electric locomotives, the cost of these for repairs, inspection, shed wages, lubricants, stores and clothing was less than one-third of that for the steam locomotives.

APPENDIX 2.

Cost of Replacement of Steam Locomotives by Electric Locomotives.

It is an almost essential condition of successful financial results in main-line electrification that the provision of the electric locomotive stock should be chargeable to revenue. This would be impossible were it not for the greater annual mileage obtainable from the electric locomotive.

Locomotive or other machinery renewals, if paid for from revenue, should be made on a basis of replacing like with like. The locomotive renewals effected annually on a railway should leave the total haulage capacity of the locomotive stock unaffected. Variations in prices should not affect this principle and, taken year by year, the sum expended on renewals should fluctuate. In actual practice this is inconvenient and, in many cases, it is usual to set aside a fixed sum, making adjustments for minor fluctuations in prices by deferring renewals in dear years and accelerating them in cheap ones, while unforeseen extreme fluctuations such as those caused by the war are dealt with specially and in relation to other factors such as fluctuations in receipts arising from the same cause.

For the purpose of this paper, however, the author assumes in the first instance that electrification is being carried out solely to reduce working expenses and that, consequently, the haulage power of the locomotive stock will not be increased in the aggregate, at any rate appreciably.

From the figures given below it will be seen that the assumption is not necessary because, if on a mileage-per-annum basis one electric locomotive can replace two steam locomotives, the cost of replacement of equal haulage power will be less for electric than for steam locomotives.

Apart from any question arising from an accountancy point of view in connection with the ratio of pre-war and present-day costs, the provision of the electric locomotives necessary will therefore not be a charge against capital.

The 4–6–0 four-cylinder steam locomotive, No. 3 in Table 2, is a typical express passenger tractor; its weight empty is 92 tons, and its current market value at present prices at £80 per ton is approximately £7 500. Its electrical equivalent type might be taken as No. 8 in the same table, namely, weight 90 tons and 2 100 horse-power on 1-hour rating, the cost of which would be approximately as follows :—

		£
2 100 h.p. of motors at £2·5 per h.p.	..	5 250
Control and cabling at £1·2 per h.p.	..	2 520
Vacuum pumps, motor-generator, etc.	..	1 000
55 tons of locomotive structure at £75 per ton		4 125
		£12 895

i.e. £143 per ton.

$$\text{And ratio} \quad \frac{\text{Electric locomotive cost}}{\text{Steam locomotive cost}} = \frac{1 \cdot 72}{1}$$

If the steam passenger locomotives averaged 26 000 miles per annum, then for the fixed charges to be the same the electric locomotive mileage would have to be 44 750 miles per annum; excluding Sundays and 26 days per annum for examination and repairs, the daily mileage would have to be 156.

The steam and electric freight engines may be compared on the basis of the 0–8–0 shown as No. 11 in Table 2, and the 4–4 electric Midi Railway No. 15 in the same table. The weight of steam locomotive empty is about 78 tons, and its current market value at £80 per ton approximately £6 240. The cost of the electric locomotive, weight 70 tons, will be approximately as follows:—

		£
1 400 h.p. of motors at £2·2 per h.p.	..	3 080
Control and cabling at £1·5 per h.p.	..	2 100
Vacuum pumps, motor-generator, etc.	..	1 000
48 tons of structure at £75 per ton ..	..	3 600
		£9 780

i.e. £140 per ton.

$$\text{And ratio} \quad \frac{\text{Electric locomotive cost}}{\text{Steam locomotive cost}} = \frac{1 \cdot 56}{1}$$

If the steam freight locomotive averaged 18 300 miles per annum, to obtain equality in fixed charges the electric locomotive would have to average 28 550 miles per annum, or 100 miles per day on the same basis as the passenger locomotive.

This electric locomotive could haul 720 tons, trailing, up a 1 in 100 grade at 26 m.p.h. The test load was 254 tons up 1 in 30 at 28 miles per hour.

If the 0–6–0 steam freight locomotive, the empty weight of which is 56 tons and the cost at present prices £4 480, were replaced by an electric locomotive 0–4–4–0 of similar draw-bar h.p., viz. 800 h.p. at the 1-hour rating, the cost of the electric locomotive would be:—

		£	Weight, tons
Four 200-h.p. motors, control and cabling		4 400	18
2 bogies and gear cases	..	1 125	14
Structure 25 tons at £75 per ton..	..	1 875	25
		7 400	57

i.e. £130 per ton.

$$\text{And ratio} \quad \frac{\text{Electric locomotive cost}}{\text{Steam locomotive cost}} = \frac{1 \cdot 65}{1}$$

The tractive effort of the locomotive at 30 m.p.h. would be 12 000 lb., corresponding to a haulage capacity of 290 tons up a 1 in 100 grade, and 570 tons on a 1 in 300 grade at 32 m.p.h.

If it is correct that double the mileage can be found by the traffic department for a day's work for an electric locomotive as compared with a steam locomotive (for there is no doubt about the capacity of the electric locomotive to treble the steam-engine mileage if necessary), there is then, on the basis of replacing like haulage capacity with like, a very considerable margin for building larger electric locomotives to replace the steam locomotives, and at no greater cost than would have been involved in normal steam-locomotive renewals.

The question of the allowance to be made in the future for the obsolescence and life of the electric locomotives is also of interest. The usual assumed life of a steam locomotive is 40 years. There seems little doubt, judging from the results obtained on the Liverpool and Southport line and on the District and other early electrified lines, coupled with consideration of modern improvements in design, that the life of the electric locomotive will be just as great as, or greater than, that of the steam locomotive. It is probable, indeed, that whereas the steam locomotive 40 years old consists of hardly more than the original brake rods and, possibly, frames and wheel centres, the rest having been renewed, after 40 years the electric locomotive will exist *in toto* as built. As regards obsolescence, after a certain stage has been attained in the development of a new invention a measure of finality is arrived at and obsolescence is slow until some further complete innovation replaces the original. The older a method the higher should be the rate of obsolescence. There is therefore no sound reason for assuming at the outset any different life or rate of obsolescence for electric locomotives than for steam, though after more extensive experience the life may be increased and the rate of obsolescence reduced.

APPENDIX 3.

The question of the density of traffic is of such importance in connection with the cost of current for main-line electrification purposes that it is desirable to set out in some greater detail the comparative figures for the year 1922, in connection with the traffic density on one of the former large independent railway systems which carried the heaviest traffic and one of the suburban electrifications.

Coaching train-miles ..	..	..	..	20 480 890
Coaching shunting-miles	..	..	..	1 466 705
Freight train-miles ..	..	..	..	22 085 909
Freight shunting-miles	..	..	..	12 087 646
Assisting coaching-miles	..	..	..	632 846
Assisting freight-miles	..	..	..	2 943 450
Light mileage	..	..	..	2 605 576
Departmental mileage	..	..	..	2 041 550
Total engine mileage			..	64 344 572

No. of single-track miles exclusive of sidings	3 568
Miles of sidings	1 831
Freight and coaching train-miles, excluding shunting, light, departmental and assisting miles	42 566 799
Train-miles only per track-mile, exclusive of sidings	11 900
Total engine-miles per track-mile, exclusive of sidings	18 000
Shunting-miles, coaching and freight per siding-mile	7 400
Coal per engine-mile, passenger services ..	47·14 lb.
Gross weight of passenger train based on 0·175 lb. per ton-mile	270 tons
Coal per engine-mile, freight services ..	58·35 lb.
Gross weight of freight train based on 0·175 lb. per ton-mile	334 tons
Gross coaching train ton-miles, 20 480 890 × 270	5 530 millions
Gross freight-train ton-miles, 22 085 909 × 334	7 380 millions
Total gross train-ton-miles on running lines excluding sidings (average gross train weight 304 tons)	12 910 millions
Gross train-ton-miles per track-mile per annum, excluding sidings	3 620 000
High-tension kWh per track-mile, excluding sidings, at 45 watt-hours per ton-mile ..	163 000
High-tension kWh per substation per annum with 10 miles of 4-track route fed from one substation	6 570 000

Comparative Figures for Suburban Electrified System.

	1922
Train-miles	2 264 732
Ton-miles	360 433 418
Average train weight (tons)	159
High-tension kWh used for traction ..	43 335 972
Track-miles electrified	121
Train-miles per track-mile	18 700
Ton-miles per track-mile	2 980 000
High-tension kWh per track-mile	362 000
Average high-tension kWh per substation per annum (average suburban electrification)	5 500 000

These figures clearly show that, excluding shunting, assisting, light and departmental mileage, the average train-ton-mile per track-mile density on the large steam-operated system is 20 per cent greater than on the electrified suburban system, but that owing to the lower energy consumption per ton-mile for the former the electrical demand density is only 45 per cent of that for the electrified suburban lines.

As the load factor on the substations for the steam-operated system would be much better than the load factor for the electrified suburban lines, owing to the all-night freight traffic which does not exist on the latter, the kilowatts of substation plant per track-mile required for the steam-operated system would be less than half of that required for the electrified lines. An average figure for electrified suburban lines with this traffic density is about 180 kW of rotary converter plant per track-mile, and the amount of converter plant required for main-line work will therefore be about 90 kW per track-mile; but the provision necessary for the power for shunting mileage will probably raise this figure to 120 kW.

As, however, the suburban electrification figures given above represent track, most of which is operated at 600 volts, and the main-line electrification would be carried out at 1 500 volts, it is fair to assume that the distance between substations would be at least three times as great for the main line. In these circumstances the total annual output of the main-line substations would be higher than for the suburban system, though the maximum loads would be smaller owing to the better load factor.

APPENDIX 4.

Notes in regard to Table 7.

Steam Locomotives.

Results.—The results are all calculated from figures obtained from dynamometer-car records.

Tractive resistance.—The total tractive resistance of the train in lb. per ton on the various runs is obtained by dividing the average tractive effort whilst doing positive work, by the weight of the train hauled.

The resistance of the train on the level has been taken from curve 4 in Fig. 5 (derived from recent tests on L.M. and S. passenger stock—weight of train 435 tons); and that of goods trains on the level from curve 2 in the same figure.

The resistance due to gradient, etc., is the difference between the total resistance and that on the level.

The total tractive resistance of the engine in lb. per ton is obtained by taking the resistance on the level at the average speed whilst doing positive work (as given in Fig. 5, curve 1), plus that due to gradient obtained as above.

Horse-power and h.p.-hours.—Draw-bar horse-power and draw-bar h.p.-hours are taken from the dynamometer car records, the energy to overcome the total tractive resistance of the engine being added to give the gross horse-power and gross h.p.-hours.

Ton-miles.—The total ton-miles include the weight of engine and tender (gross ton-miles), and the trailing ton-miles exclude the weight of engine and tender.

Coal consumed.—The coal consumed between terminal stations (excluding shed duties) and the total coal used (including shed duties) are given. The average of the laboratory tests over a period of two years on classes of coal similar to that used in these tests gave a carbon content of 58·23 per cent, volatile matter 32·74 per cent, ash 9·62 per cent, sulphur 2·48 per cent, evaporative power 13·88 lb. of water per lb., calorific value 13 481 B.Th.U.'s per lb.

Mechanical efficiency.—This is obtained by dividing the draw-bar horse-power by the gross horse-power.

Thermal efficiency.—This is equal to

$$\frac{\text{h.p.-hours} \times 33\,000 \times 60 \times 100}{\text{B.Th.U.'s in fuel per lb.} \times 778 \times \text{coal consumed}}$$

and is considered in the table under the following conditions :—

(*a*) Gross h.p.-hours and coal consumed (excluding shed duties).
(*b*) Gross h.p.-hours and total coal consumed (including shed duties).
(*c*) Draw-bar h.p.-hours and coal consumed (excluding shed duties).
(*d*) Draw-bar h.p.-hours and total coal consumed (including shed duties).

Electric Locomotives.

Results.—The same energy is required to haul the trains as in the case of the trains hauled by steam locomotives. The author has taken the case of a 116-ton electric locomotive, this being more than capable of dealing with requirements.

Tractive resistance.—The total tractive resistance of the electric locomotive is obtained by the addition of the following :—

(*a*) Resistance of the locomotive as a vehicle, taken from Fig. 5, curve 3. This curve is an average of the results given by Mr. Carus Wilson and Mr. Carter, and does not include the resistance of gears and motor bearings (this resistance being included in the overall efficiency of 66·6 per cent from power station to tread of driving wheel).
(*b*) Resistance due to gradient, etc.

Coal consumption.—The coal consumption at the power station is arrived at by taking the total h.p.-hours required for the engine and train, converted to kilowatt-hours, and an overall efficiency of 66·6 per cent has been taken to obtain the equivalent kWh at the power station.

A figure of 1·98 lb. of coal per kWh output from the station has been used (Dalmarnock power station, March 1923), the calorific value of the fuel being taken as 11 000 B.Th.U.'s per lb.

Description of runs.

16 *Passenger runs*—Manchester to Blackpool.

On the outward runs the respective heights above sea-level of start and finish were 110·28 ft. and 68·62 ft., the first 5 miles being a stiff up gradient of approximately 1 in 130, whereas on the return run the length of approach to this maximum point was 14 miles.

5 *Goods runs*—Crofton to Mytholmroyd, one way only.

The respective altitudes were 142·44 ft. and 328·7 ft., this giving an average up gradient of 1 in 695.

Passenger runs. 141 miles—Crewe to Carlisle and return.

Outward run—altitude at Crewe 161·86 ft., altitude at Preston 68·1 ft., highest point at top of Shap 916 ft., altitude at Carlisle 67·6 ft. The approach to Shap on the outward and return journeys is shown clearly in Figs. 3 and 4.

Passenger runs. 90·1 miles—Preston to Carlisle.

Goods runs. 90 miles—Preston to Carlisle.

The Pennsylvania Railway Company, from their rotary testing plant at Altoona, publish the results of tests on various steam locomotives as shown in Table 12. The columns giving the thermal efficiencies are calculated on the dry coal consumed during the test. It will be noticed that these figures are higher than those given by the author, this being probably due to :—

(*a*) Higher boiler pressure—250 lb. per sq. in. (against 180 lb. per sq. in.);
(*b*) The resistance at given speeds of leading, trailing and tender wheels has not to be overcome on a rotary test plant;
(*c*) No resistance due to curves, wind pressure, or track depression;
(*d*) The tests were carried out with full throttle opening and later cut off;
(*e*) Dry fuel.

Table 12.

Pennsylvania Railway Tests on Steam Locomotives.

Date of tests	Number of tests	Type of locomotive	Weight of engine	Average speed during test	Average B.Th.U.'s per lb. of fuel	Thermal efficiency	
						draw-bar h.p.-hours	i.h p.-hours
			tons	m.p.h.	B.Th.U.'s per lb.	per cent	per cent
Feb.–April 1918 ..	39	2–10–0	166	15·25	13 480	6·4	7·4
Feb.–April 1918 ..	28	2–10–0	166	18·75	15 115	4·5	5·6
Oct.–Dec. 1914 ..	29	2–8–2	141	19·25	13 980	5·5	6·4
Oct.–Nov. 1914 ..	34	4–6–2	138	52·00	14 500	6·5	7·9
Oct. 1914 to April 1918	130	—	152	26·4	14 019	5·7	6·8

APPENDIX 5.

ESTIMATE OF REDUCTION IN COAL CONSUMPTION TO BE EFFECTED BY ELECTRIC TRACTION ON ALL RAILWAYS IN GREAT BRITAIN.

Total engine-miles of standard gauge in 1922 in Great Britain = 504 916 311

Average coal consumption per engine-mile for all services = 54·04 lb.

$$\text{Therefore total coal consumed} = \frac{504\,916\,311 \times 54\cdot04}{2\,240}$$
$$= 12\,193\,776 \text{ tons}$$

or, say, 12 195 000 tons, costing £14 815 177.

Total standard-gauge mileage in Great Britain, excluding sidings = 35 088

If the coal consumption is 54 lb. per engine-mile and 0·175 lb. of coal per gross ton-mile, then gross weight of train is 54/0·175 = 308·5 tons

Total ton-miles per annum = 308·5 × 504 916 311
= 155 400 millions

Watt-hours per ton-mile = 30

Efficiency = 66·6 per cent

Therefore watt-hours per ton-mile at power station = 45.

Coal consumed = 1·98 lb. per unit.

Therefore total coal

$$= \frac{155\,400\,000\,000 \times 45 \times 1\cdot98}{1\,000 \times 2\,240} = 6\,180\,000 \text{ tons}$$

Average saving per annum in coal = 6 010 000 tons.

COAL CONSUMED ON RAILWAYS IN GREAT BRITAIN IN RELATION TO THE COAL RAISED IN GREAT BRITAIN, 1922.

Total coal raised in Great Britain in 1922 = 249 607 000 tons

Coal used for railway operation = 12 193 776 tons

Coal used for railway operation represents 4·9 per cent of coal raised.

Coal saved by electrification of railways = 6 010 000 tons.

Coal saved by electrification of railways represents 2·4 per cent of coal raised.

DISCUSSION BEFORE THE INSTITUTION, 27 MARCH, 1924.

Mr. R. T. Smith: The author claims that the density of main-line traffic is greater than that of the corresponding suburban traffic, and he states one reason for this to be the fact that trains on a busy main line are running throughout the 24 hours, whereas on the suburban lines they are limited to 17 or 19 hours. He gives his unit of comparison of cost as the engine-mile. Personally I have always considered that any unit of comparison for electrification should be on the basis of the engine, but I doubt if the engine-mile is the most convenient unit. As the author points out, it takes no account of speed, or weight, or number of stops. It is extraordinarily difficult to manufacture any unit which will allow a satisfactory comparison to be made between the cost of different traffics. Probably the best unit would be some such compound unit as "ton-miles per engine-hour." Although I have not worked out the author's figures on that basis, I have found that such a unit gives much more uniform results. However, properly interpreted the engine-mile is quite a satisfactory unit of cost. The author's unit of density is the trailing ton-miles per mile of track per annum, but the engine-miles per track-mile per annum, from which his unit is derived simply by multiplying by an assumed constant weight of train, appears to me to be really a more convenient unit to deal with. It is very inconvenient to deal with a unit which is in millions. Table 7 gives actual steam-locomotive test figures compared with partly assumed and partly actual electric locomotive figures, and the comparison between steam and electric locomotives in Fig. 8 for various traffic densities is based on certain assumptions which are now, I think, quite agreed among electrical engineers. On pages 749 and 750 the author summarizes the conclusions which he draws from the figures given, namely that it would pay to electrify main lines above a certain density of traffic, which comes out at above 3 million trailing ton-miles per mile of track per annum. The author omits to mention, however, the great traffic advantage of the speed characteristic of the electric motor as compared with that of the steam engine. This has been specially brought out on the Italian State Railways, where nearly all the electrification is three-phase with two fixed speeds, although four speeds can be used where necessary. It was thought at first that uniform speed was a disadvantage, but it was found that the constant speed and the fact that, for most of the traffic, the speed of the slow freight traffic was half that of the fast traffic, was most satisfactory. It has been pointed out that one of the advantages of electrification on main lines even with direct current is that all the passenger traffic can be run at practically one speed and all the freight traffic at half that speed. In view of these and other advantages, and the fact that France contemplates electrifying in its complete programme 5 600 miles of track (or one-third of the whole of the railways in France), that Italy contemplates electrifying 2 800 miles of track, and that Switzerland within a few years will have electrified 1 000 miles, how is it that we have comparatively no main-line electrification in this country? The first and obvious answer is that in all those countries, even in the greater part of France, coal is an import, while there is sufficient water power to run the railways, and it is worth while to do so from the national point of view simply to prevent the import of coal. Apart from that, however, I cannot but feel that electrification is going on in those countries largely because it has become the fashion. Railway electrical engineers are, I think, more or less convinced that beyond a certain density it would pay to electrify main lines in this country; but the traffic officers are not yet convinced, and a good many of the traffic officers do not want to be bothered with it. I am quite convinced that if any one traffic

officer could be induced to put his heart into the thing —because, it is to be noted, nearly all the real troubles devolve on the traffic officers, and it is they who will have to change their methods—and if the fashion could be set by one railway starting any considerable amount of main-line electrification, the rest of the railways would follow suit.

Mr. F. Lydall: The question of the unit of comparison to be adopted is an important one, and I should like to support the author in bringing forward the unit of "trailing ton-miles per track-mile." It is true that it is rather a clumsy expression, especially in comparison with the simple straightforward unit of "engine-mile," but, after all, one cannot get very far in considering any scheme without leaving aside the engine-miles and studying the actual ton-mileage. Ton-mileage represents the work which is to be done; the engine mileage can only do so on a convenient convention that to every engine is allotted a certain tonnage haul. Therefore, whatever may be the general practice, the unit of ton-mileage to be hauled must be used and developed. The author gives certain figures of average tonnage behind the draw-bar, and those of us who follow the developments in other countries, especially in the United States, must be struck by the extraordinary difference that there is between these weights and those which are hauled on other lines. Railway engineers in the United States are getting accustomed to talking of loads of 2 000 to 5 000 tons. The figures given by the author for British railways are perhaps a quarter or a fifth of those. I suppose it is not unreasonable to hope, however, that some day, even in this country, we shall develop to a point at which we shall have a substantial increase of the loads which the author has mentioned. We cannot go on for ever economically hauling 200 or 300 tons of goods with a single engine, a guard, and all the other necessary accompaniments to a complete train. When the time comes for the average load to be doubled, trebled, or even quadrupled, any comparison on the basis of engine-miles at that time with figures of engine-miles at the present time will be completely fallacious. On the other hand, the comparison on the basis of trailing ton-miles will remain exactly the same. The author sets out very convincingly the relative advantages and disadvantages of electric and steam locomotives. Practically the only disadvantage of the electric locomotive that he mentions is that a large number of units may be immobilized owing to the failure of the electric supply. That is perfectly true, but the whole question is what weight to attach to that particular disadvantage: how often have a large number of electric locomotives been immobilized for this reason? I had occasion about three years ago to consider such a point as this, and I was able to obtain, through the kindness of the engineers of the Newcastle Electric Supply Co., some information as to the operation of the Tyneside lines of the North-Eastern Railway which receive power from the Newcastle Supply Co.'s system, and also the mineral line between Shildon and Newport. The records were for a period from 1905 until 1920 and the result was that, on the average, so far as the Tyneside line was concerned, there was interruption of traffic, due to disturbance in the high-tension supply to the substations, on the average only once every two years, and the duration of those interruptions was quite short—a few minutes only. The experience with regard to the Shildon and Newport line for five years was much better, and therefore it was not considered worth while to go through all the records and take out the figures. I have no doubt that the record for the last five years only would be considerably better than that. I think, therefore, that one may claim that on a modern power system, developed in modern ways with protective apparatus and an extensive network, and so on, the interruptions of supply causing stoppage of traffic can be regarded as being genuinely negligible. I should like to ask the author what curve 1 in Fig. 5 represents. I take it that the train resistance of a steam locomotive is derived from the difference between the indicated horse-power and the draw-bar horse-power. On the other hand, I suppose that the train resistance of an electric locomotive is derived from the difference between the brake horse-power exerted by the motors at the treads of the driving wheels, and the draw-bar horse-power. Again, the resistance of a 10-ton wagon (curve 2) at one particular point is given as 15 lb. per ton at 40 m.p.h. This question of train resistance is a very difficult matter, owing largely to the diversity of conditions under which the tests have been made, and the difficulty of correctly interpreting the results obtained. I had an opportunity in South Africa a few years ago of carrying out some very careful tests on goods trains, under conditions rather different perhaps from those customary in this country, but I found that there was a very marked difference indeed between the train resistance of a goods wagon when it was fully loaded and when it was empty. A goods wagon in South Africa is usually a four-wheeled, double-bogie wagon. On the occasion when I made the test the average load per axle varied between 11 short tons and 3·4 short tons; that is to say, the 11 tons represented a loaded 44-ton wagon and the 3·4 tons represented the same wagon empty. The train resistance of the loaded wagon was only about 8 to 9 lb. per ton at 40 m.p.h. The resistance of the same wagon when running light at the same speed was between 24 and 26 lb. per ton. The difference between these figures shows that a good deal of care has to be taken in referring to the train resistance of wagons, because the weight of the wagon itself varies so much. I should be glad if the author would indicate under what conditions curve 2 (which refers to the 10-ton wagons) was taken. Again, curve 4 represents the train resistance of a 435-ton passenger train. In my experience, the train resistance there shown corresponding to 60 m.p.h., viz. 15 lb. per ton, seems to be rather high. Possibly the author has intentionally included a considerable margin for bad weather conditions. A test was made some few years ago on the New York Central Railway with one of their gearless locomotives and 9 passenger cars. At 80 m.p.h. the train resistance was 11·4 lb. per short ton, which is very much lower than the figures given by the author. These figures of train resistance are of great importance when studying the electrification of a main line, because they vitally affect the calculation of energy con-

sumption. On a straight run, with no complications, no curves, no starts, no stops and no gradient, the watt-hours per ton-mile at the draw-bar are directly proportional to the train resistance. In fact, watt-hours = (train-resistance in lb. per ton × 2). For example, if the train-resistance is 10 lb. per ton, the number of watt-hours per ton-mile is exactly 20. In Appendix 1 the author gives some valuable information in regard to the mileage worked by electric locomotives, and the corresponding reduction which is possible in the number of locomotives on an electrified line compared with steam-working. A statement was recently issued, with regard to the electric locomotives on the New York, New Haven and Hartford Railway, to the effect that for the last 17 years, 41 single-phase locomotives constructed by the Baldwin and Westinghouse Companies had each of them on the average worked more than 70 000 miles per annum. On the St. Gothard line some electric locomotives doing three shifts per day of 24 hours—that is to say, assuming there is not far short of 8 hours per shift, they practically work all round the clock—accomplish 435 miles in the 24 hours. The Chicago, Milwaukee and St. Paul Railway has published certain figures which are not mentioned by the author. Mr. Storer stated in 1921 that the record for a continuous 24-hour run on one of the passenger locomotives supplied by his company to this railway was 766 miles. Soon after that a statement was made in the *Railway Gazette* to the effect that "the electric passenger locomotives put into service a year ago make 440 miles run with one engine. During this run they stop at Deer Lodge and change crews. The locomotives are taken off for shop inspection after a mileage varying from 3 000 miles to 5 000 miles, that is, they are inspected every 8 or 10 shifts. Under this operation locomotives have been making records of from 10 000 to 11 000 revenue miles per month." Those figures, of course, are very high compared with any figures that can be obtained in connection with steam locomotives. The only conclusion one can come to with regard to electric locomotives is that the mileage which they can run in the year depends mainly upon the opportunity they have for doing work. If traffic arrangements are suitable, the electric locomotive can, I have no doubt, do anything up to 100 000 miles per annum. If the traffic arrangements are not suitable, it is obvious that, due to long periods of lie-over, fluctuation of traffic and so on, the mileage per locomotive is proportionately reduced.

Mr. F. W. Carter: The author mentions on page 739 that his costs of fuel, and so on, are based on three-phase generation, overhead line transmission, conversion by mercury-arc rectifier, and third-rail distribution to train. Of course some of these factors might be varied without making any particular difference to the results given in the paper. The author mentions on page 748, however, that overhead transmission lines should be taken separately to the substations and not run along the track. I think that the expense would thereby be considerably increased. The author takes the cost of third-rail track equipment in Table 9 as £2 500 per mile, which is, I think, a reasonable figure as it includes special work, but I am not sure whether it includes the moving of the signal rods and other obstacles, which often adds considerably to the cost of the electrification. Whether one uses a third rail or an overhead line is largely a matter of opinion, and probably both will be used on main-line railways in different parts of the country. In Table 5 the author gives the cost of electrical energy delivered to the high-tension lines. Is the last column but one, headed "Typical railway power station supplying suburban electrification," based on an actual case or are the figures estimates? In Fig. 8 the author gives certain curves showing the reduction in operating expense in electrical working as compared with steam, the price of energy being assumed to be 0·4d. and 0·5d. per unit, and I am pleased to see that even in the latter case he makes out a very good case for electrification on most of our main-line railways. In Table 6 he gives efficiency figures which do not agree with Mr. Roger Smith's and Mr. Parodi's figures as regards transformation and conversion. I think, however, that the author's figures are probably the more correct, i.e. that the efficiency of transformation is higher than is generally supposed. Take, for instance, a unit consisting of a rotary converter, with transformers, which is in service represented typically by one hour without load, one hour at one-tenth load, one hour at half load and one hour at full load, with overall efficiencies given in the table below. The total energy output (i.e. load × hours) is 1·6 and the input 1·774. The average efficiency of transformation is therefore 90·2 per cent, with a load factor of 40 per cent.* The main value of the paper in my view

Load	Efficiency	Loss	Time	Output	Input
	%				
0	0	0·030	1	0	0·030
$\frac{1}{10}$	76·0	0·032	1	0·1	0·132
$\frac{1}{2}$	92·0	0·043	1	0·5	0·543
1	93·6	0·069	1	1·0	1·069
		Total ..	..	1·6	1·774

lies in the connection that it establishes between steam and electric working, largely as a result of the careful train tests recorded in Table 7.

Mr. J. S. Highfield: I agree with Mr. Roger Smith that it is a matter of the first importance to interest traffic officers in the value of electrification from a traffic point of view. The author's figures showing the saving in cost by electrification are, of course, of great importance, but, even taking into consideration all that Mr. Lydall has said in regard to the long life of electric locomotives and their capacity to run so many hours of the year, I do not think it at all likely that electrification will be adopted merely to reduce the working expenses. Of course, part of the saving consists in reducing the consumption of coal to approximately one-half as compared with steam locomotives, and this, possibly, might be held to be a matter of national importance, but I do not think so. Therefore, we must

* F. W. Carter: "Railway Electric Traction" (page 382).

look to other reasons than merely the saving in cost for carrying out main-line electrification. If we consider suburban railways, the main reason for electrifying was to enable the lines to carry heavier traffic. Either the traffic grew from natural causes or, alternatively, it was considered that the electrification of a particular line would lead to greater traffic, and this has proved to be true in every case where suburban railways have been electrified. We have no examples of main-line electrification in this country, but if we study the causes that have brought about main-line electrification on the Continent, we find that, in Northern Italy for example, the chief causes were, first, the desire to use water power; secondly, that the load which many of the bridges could carry was strictly limited and, consequently, the weight of steam locomotives could not be increased to deal with additional traffic; and thirdly, that electric locomotives enabled greater loads to be carried at higher speeds without the expense involved in strengthening the bridges. In France, again, there was the desire to use water power to provide a broadcast system of electric distribution for other purposes, and this system naturally worked in well with the development of water power for railway purposes. There was, in short, a combined desire to supply the country with cheap electricity developed from water power and to run the railways without the necessity of importing coal. Also in Japan, where the gauge is 3 ft. 6 in., the easiest method of increasing the carrying capacity of the lines was to electrify in all cases. Therefore, there were extraneous reasons for carrying out electrification, apart from the mere saving in cost. I understand that in all these cases numerous other advantages have resulted, such as increased carrying capacity and increased speed. I think it likely that main-line electrification in this country will ultimately be forced on the railways in order to enable existing terminals and tracks to deal with the heavier traffic and at increased speed. No doubt the increased speed and facilities generally will again react by increasing the traffic.

Mr. A. E. Jackson:* The author gives on page 729 a definition of the engine mileage on a system as the actual number of miles run by all steam tractors whether hauling trains or running light. I should like to ask him whether the steam-locomotive engine-mile mentioned in Tables 1 and 3 is the gross mileage (i.e. all mileage including running for locomotive requirements) or whether it is a net mileage. It would not be fair to compare the cost per gross steam-engine-mile with the cost per electric train-mile. I take it that the last column of Table 1 should in any case refer to the net train mileage. In Table 3 the cost per engine-mile of superintendence is compared for steam and electric working, and it is stated that there is "No change"; but surely if the electric locomotive performs double the mileage per day that a steam locomotive does, the cost of superintendence would be reduced, if not by half, at any rate to a very great extent. With regard to the general question of electrification, the author on page 755 says that the resulting saving in coal is over 6 million tons per annum. If that is so, it seems to me that this is really a national question apart from all other aspects. It may be noted that this quantity of coal would be capable of generating some 7 000 million units of electricity per annum.

* In addition to making these remarks, Mr. Jackson read Sir Philip Dawson's contribution to the discussion (see page 758, col. 2).

Mr. R. Brooks: One very important point which the author makes, and one which I had not quite appreciated before, is that the density of main-line sections is very much in excess of the traffic density on suburban sections which have already been electrified most successfully. The question of standardization has already been mentioned in the course of previous discussions. In most cases the criticism was aimed largely at the manufacturers, but I think that early standardization is to be avoided. Closely bound up with this question of standardization is the matter of simplicity of equipment. It seems to me that very soon we shall be prepared to sacrifice, for the sake of getting simplicity and robustness of equipment, a great many of the refinements which are being demanded at the present moment. After all, we use electrical equipment for the sake of getting efficient transportation, and our whole energies should be directed towards obtaining an equipment which will have the minimum of parts and the minimum of complexity to achieve that object. The author mentions different types of locomotives which may be used to meet the different services, and deals solely with four-motor combinations. This is sound in so far as obtaining a standard type of control is concerned—and that is very important. One has to consider the different capacities of the motor which will have to be controlled and, although it may at first sight seem difficult, it should be perfectly possible, with a properly-designed line of apparatus, to retain the advantages of the unit form of construction—to retain the major elements of the equipment exactly the same, and simply vary the copper content to meet the different requirements of current capacity. The author's summarized conclusions give a very clear picture of what may reasonably be expected from the electrification of main lines. When we consider how conservatively he has arrived at his figures, and the fact that he has not claimed any of the traffic advantages which have always followed the suburban electrifications, we cannot help feeling that his conclusion in the body of the paper might perhaps have been expressed somewhat more strongly than it has been. We have got beyond the region of general considerations and general investigations, and the time should soon be ripe for our railway authorities to investigate particular sections with a definite view to electrification. In conclusion I submit that the electric locomotive is no longer an experiment. Where it has been adopted under proper conditions it is an established and unqualified success, and further hesitation seems to me to savour too much of that over-caution generally attributed to my own countrymen. The record of the work already done justifies the belief that the success which has followed electrification elsewhere may also reasonably be expected in this country.

Sir Philip Dawson (*communicated*): I am sorry that the author has not given calculations for a concrete case and that the figures arrived at are only of a general

nature based on assumptions similar to those contained in another paper by Mr. Roger Smith, dealing with the same subject. I also regret that in treating the problem of main-line electrification the assumption that there is only one system available as regards type of current, working pressure and contact system, has once more been made. All who have investigated in detail the subject of main-line electrification know that much higher line pressures than those contemplated by the author are essential if the system is to be applied in a general way. Also it is to be regretted that in referring to electrification in Europe the author only quotes French practice, having regard to the limited experience so far obtained in that country and to the very extended experience in all varieties of main-line electrification available in Italy, Austria, Switzerland, Germany and Sweden. The map exhibited at the meeting shows the extent of railway electrification in these countries as compared with that in France. Until further experience is available I should also myself hesitate to regard the mercury rectifier as being necessarily the right thing to adopt in connection with main-line electrification in this country. The introduction of the transverter may materially alter conditions, and I am not at all sure that it will not militate in favour of high-tension a.c. traction. As, however, the object of this paper is, I take it, to show that main-line electrification may not only prove desirable but may be essential, and not merely to favour one system against all others, I endorse all that the author has put forward in favour of main-line electrification in this country. I am convinced that there are many main-line sections on British railways where electrification would prove a great financial success. It is unfortunate, but nevertheless true, that grouping has reacted unfavourably on the prospects of electrification, to the great disadvantage of the public and of our industries. The moving spirits of those railways which but for the grouping would have been in the course of carrying out not only suburban but also main-line electrification have disappeared. Sir Henry Thornton and Lord Claud Hamilton had decided to electrify the whole suburban area around Liverpool-street. Sir Vincent Raven and his advisers had prepared a complete scheme for electrifying the main line from York to Newcastle. The late Lord Bessborough, Mr. Charles Macrae and Sir William Forbes had told their shareholders that they intended to electrify not only the whole of their suburban system but also the main line to Brighton, Worthing and Eastbourne. Indeed, the adoption of the single-phase system was based on the express intention to electrify the main line. Before the war the Caledonian Railway was considering the electrification of its system around Glasgow. Now that grouping is completed, we find that the London and North-Eastern Railway not only has no intention of electrifying the main line from York to Newcastle but do not intend to electrify the suburban sections around Liverpool-street and to Tilbury, and the Chairman of the North-Eastern Railway Company, although not satisfied with conditions on the suburban lines, can see no immediate cure except by carrying out widenings and reverting to the policy of railways 20 years ago in the early days of tramway and motor-omnibus competition. Having regard to the importance of the problem, a few conclusions resulting from a complete investigation that I carried out in co-operation with the Locomotive, Goods, Accountancy and Traffic Departments of the London, Brighton and South Coast Railway, and approved by all the departments concerned, may not be without interest, particularly as this investigation was subsequently checked by the highest Continental authority on this subject, who sent over a staff of engineers and, after investigating the whole problem, confirmed the conclusions at which I had arrived. This double investigation took nearly two years to complete and was carried out in the greatest detail, involving the preparation of a complete scheme for electrification in all its details. All the figures were based on statistics for 1920 and 1921 and the summer of 1922. The investigation comprised (*a*) the electrification of the whole suburban system, all goods and main-line trains being run by steam; and, alternatively, (*b*) the electrification of all services in the suburban area and on the main line as far as Lewes, Brighton and Worthing. The basis on which calculations for the capital and operating costs were made was that the seat-miles per annum should be increased by 140 per cent for the suburban and 70 per cent for the main line, this being obtained by more frequent services and by operating the trains at the various hours of the day to meet the passengers to be accommodated. It was shown that an increase in gross receipts of 58 per cent on the suburban and 29 per cent on the main line would give a return of over 8 per cent on the capital involved, and for an increase of 100 per cent on the suburban and 50 per cent on the main line—which the management was convinced would be achieved—a return of 15 per cent would be obtained. The plant provided and the operating costs included, for both cases, an increase in travelling facilities of 140 per cent on the suburban and 70 per cent on the main line. The capital expenditure provided for:—

- The electrical equipment of all tracks and sidings; the transmission lines and substations; altering telephones and telegraph circuits and signalling system, comprising in all the equipment of (in round figures) 500 miles of single track.
- All the motor coaches and electric locomotives required, no allowance being made for the value of the steam locomotives going out of service.
- Wiring of trailer coaches and electrical equipment of driving trailers.
- Necessary additional repair shops and carriage sheds.
- Alterations to tracks, stations and bridges rendered necessary by electrification.
- Additional track facilities, junctions and other permanent way and station alterations required to handle increased traffic.

Engineering and unforeseen expenses were added to the total costs mentioned above, and interest during construction was also provided for. The total figure on the above basis came out (at costs then prevailing) at, in round figures, £11 800 000. A comparison was first made on the basis of electricity replacing the existing steam services, no increase being

provided for. This is an absurd assumption and unfavourable to electrification, as the reduction in the capital cost is relatively small compared with that required to increase the traffic as provided for in the estimates. Even under these conditions, however, a net annual saving in total operating costs of £626 700 was shown over steam. If it were possible—which it is not (without the heavy capital expenditure required for very greatly increasing the track facilities)—to increase the steam services to the same extent as the electric services provided by the full scheme, then there was shown a saving in operating expenses of £1 608 000 in favour of electric haulage. On the basis of electrifying the suburban and main line already referred to, a balance sheet was drawn up supposing that the proposals had been in operation in 1921, allowance being made for increase in maintenance of ways and works, carriages and of all portions where electric equipment as well as the increased service would increase the expenditure. This showed, based on 140 per cent increase on suburban and 70 per cent on main-line facilities, an increase in net receipts above those with the existing steam plant of over two million pounds. The most interesting part of the investigation was that it proved conclusively that by far the best paying portion of the whole proposition was the electrification of the main line to Brighton, as will be shown by the following figures:—

The ratio of the capital required for the suburban electrification to the additional capital required to electrify to Brighton was 7 : 4.

The ratio of the total operating costs of the suburban to the main-line service was 7 : 3.

And the ratio of the net receipts arising from an increase in gross receipts of twice as much on the suburban as on the main line was 7 : 6.

This shows that the increase in the net receipts on the main line is in a greater ratio in actual money than the capital and operating costs, and the main line is therefore by far the most remunerative portion of the electrification. In taking, for purposes of comparison, the average steam locomotive costs over the whole railway, there is, I think, a great danger of drawing false conclusions and, further, of presenting the case of main-line electrification in a much less favourable light than it would appear had the comparison been made with the actual costs of steam-working on those portions of the system for which electrification could be profitably considered. I think it is unfortunate that anyone casually looking at Tables 10 and 11 would draw conclusions adverse to main-line electrification, due to the fact that the figures are based on averages over the whole system, and no one at the present time would contemplate the electrification of all the railway systems of the country. The investigation which I carried out showed clearly that it was not safe to base conclusions on average steam locomotive costs, and that, including the cost of drivers and stokers and also of guards and shunters, there was a very large difference in the locomotive costs per train-mile for suburban, main-line, local goods, shunting and main-line goods trains. On the line that I had under consideration the passenger traffic was by far the greatest. The total passenger traffic on the line proposed to be electrified amounted to just over $9\frac{1}{2}$ million train-miles, as compared with $1\frac{3}{4}$ million train-miles for goods. The local lines accounted for 835 million ton-miles for passenger and 129 million ton-miles for goods services; and the main line for 1 237 million ton-miles for passenger and 415 million ton-miles for goods services. It may be of interest to state that the electrification of the main line as proposed only involved two substations in addition to those required for the purely suburban services. The results recently published by Dr. Wechmann, the Chief Electrical Engineer of the German Federal Railways operating the electrified line Halle–Madgeburg–Leipzig, fully confirm the great financial benefits to be derived from main-line electrification over level country and where electric power is generated by steam. The results which I have investigated in the United States and those achieved on the Continent of Europe, where main-line electrification is much more advanced than in America, clearly demonstrate the great benefits which under suitable conditions may be expected in this country. Incidentally, it may be mentioned that the electrification of the Liverpool-street terminus in London would render free for building purposes an area of some 10 acres in the heart of the City of London of a monetary value which cannot be ignored. The electrification of the Birmingham area would also render it possible to build over the approach to New-street Station, and many other similar examples will at once suggest themselves. Such advantages indirectly resulting from electrification are well realized in America, as evidenced by the Pennsylvania and New York Railway terminal buildings in New York City.

Mr. F. Gill (*communicated*): The author hurts a good cause by saying: "It is an almost essential condition of successful financial results in main-line electrification that the provision of the electric locomotive stock should be chargeable to revenue" (see Appendix 2). While there are probably errors in the detailed application of what follows, it shows the correct approach to this part of the problem. Taking the first cost of the freight electric and steam engines in this appendix, viz. £9 780 and £6 240, and assuming that 100 of these steam locomotives are to be superseded at the same time, such an operation would need £978 000, less what was obtained from the sale of the old steam locomotives, and it would apparently be an impossible proposition, as well as an unsound one, to charge this amount to revenue. A company is entitled to charge to capital that which fairly represents its assets; at the end of the assumed transaction, therefore, the first cost of the displaced steam locomotives should not be represented in the capital account and the entire first cost of the new electric locomotives should be so included. Taking the same 100 locomotives, this requires that the capital account be increased by (£9 780 — £6 240) 100 = £354 000. The facilities (i.e. mileage) obtained by reason of the change has nothing whatever to do with this question of what it is proper to charge to capital. Let us make the following assumptions for each steam locomotive: First cost £6 240; life 40 years; age 15 years; residual value

10 per cent; interest 5 per cent per annum; sale price at 15 years £2 080. Then the rate required for interest and depreciation (other charges such as taxes, insurance, etc., can be added as required) will be 5·7452 per cent per annum. At the end of 15 years

the amount in the depreciation fund for each such steam locomotive is	£ 1 003	
and the unexpired value of the capital is	5 237	
		£6 240
The selling price is	2 080	
There remains a *wastage*, due to the change (for which provision must be made), of	3 157	
		£5 237
and for 100 such locomotives the present loss due to this wastage is		£315 700

To put the 100 electric locomotives into service requires an expenditure of £978 000, obtained as follows:

From depreciation fund for 100 steam engines, each 15 years old	£ 100 300	
From sale of 100 steam engines ..	208 000	
From fund which is to cover wastage	315 700	
From new capital	354 000	
		£978 000

The operation of the electric locomotives has to be sufficiently advantageous to pay off this present wastage loss, viz. £315 700, and its carrying cost, as well as support the charges due to increased capital, viz. £354 000. How long will it take to pay off the present wastage loss? The answer is, in rather less than 8 years; thus:—

Present loss for 100 steam locomotives superseded	£315 700
Added capital charges:—	
£354 000 at 5·7452 per cent per annum = £20 338	
Present value (5 per cent) 8 years, £20 338 × 6·46321	131 449
Total present value 8 years	£447 149
Against this we have:—	
Saving of, say, 4·74d. per engine-mile (see Table 10, 4 000 000 ton-miles) for 36 600 miles (double that for the steam locomotive, page 752) = £722·85 per electric locomotive per annum.	
Present value (5 per cent) 8 years for 100 locomotives = 100 × 722·85 × 6·46321..	467 193
Present value of net saving in 8 years ..	£20 044

If these figures are correct, we may summarize thus:—

To change 100 of these steam locomotives the additional capital required is	£354 000
The immediate wastage charge to be financed (ultimately chargeable against revenue) is	£315 700
This wastage charge, its carrying cost and the added capital charges (for the period) will be cleared off in	8 years
After 8 years there will be a net saving per annum of	£51 947
After paying off the wastage fund, the savings to the 20th year have a present value of	£331 674

[The author's reply to this discussion will be found on page 774].

Mersey and North Wales (Liverpool) Centre, at Liverpool, 17 March, 1924.

Mr. B. Welbourn: The author has very wisely, I think, kept clear of all technical details in the paper and has taken it for granted that British engineers and firms are capable of undertaking the electrification of the British railways from start to finish as and when the demand arises. The real text around which the paper is written is the paragraph in which the author says: "It will be necessary to consider quantitative figures, for the essence of the problem is financial, and the decision whether or not to electrify portions of the British main lines will rest with financiers rather than with technical experts." The electrical engineers of this country have been convinced for some time past that a strong case can be made out for the electrification of the main lines which carry considerable passenger and goods traffic, but I am not so sure that the mechanical engineers and traffic officials of the railway companies, who have to advise their directors, are yet fully converted from their natural prejudices in favour of the steam locomotive and that they believe that a change would be financially justified. I assume that one of the author's objects in initiating this further discussion on the subject is to obtain additional information and, with this object in view, I propose to give the following particulars of some of the benefits derived from the electrification of the Chicago, Milwaukee and St. Paul Railway which were supplied to me in America in 1922. The particulars of this electrification seem to me to be of very great importance, as it is the only example in the United States of America of the conversion of a portion of a transcontinental line. A route of 650 miles, equivalent to 850 miles of single track, has been equipped for 3 000-volt d.c. operation, and the following are some of the results:—

(*a*) The trains operate with one-third less crews than formerly with steam.

(*b*) 42 passenger, freight and switching locomotives replaced 120 steam locomotives on the Rocky Mountain and Missoula division and, in 1917, handled 50 per cent more business than the steam locomotives handled in 1915.

(*c*) 15 per cent of the company's freight cars on the division were released from hauling locomotive coal and were set free for earning purposes.

(*d*) Two years' recent steam locomotive figures show that they run a daily average of 73·4 miles and spend

89 days per annum in the shops, while 15 to 28 per cent of the running time is taken in going to the ashpit on mountain grade work. The electric passenger locomotives are maintaining an average of 11 000 miles per month.

(*e*) In 1921, steam locomotive maintenance cost 33 cents per engine mile and the corresponding figure for the electric locomotive was 22 cents.

(*f*) The savings in locomotive charges are of the order of 20 per cent. In 1915, the last year of steam working, the total locomotive charges including all fixed charges were $1·2034 per 1 000 ton-miles, whereas the corresponding figure for the electric locomotive in 1917 was $0·9825.

(*g*) The smoothness in running both up and down hill on heavy grades is very noticeable as compared with steam haulage.

(*h*) The savings in brake shoes, wear on tyres and wear of the rails on curved track are quite appreciable.

(*i*) The combined demand of the Chicago, Milwaukee and St. Paul Railway and the Butte, Anaconda and Pacific Railway is 71 000 h.p. and the power factor exceeds 90 per cent.

(*j*) After allowing for all transformation losses, 11 per cent of the regenerated current is returned to the supply system.

(*k*) Where regenerative control is employed, the electric locomotive driver has much more confidence in his locomotive than in a steam locomotive, because he has the whole of the air-brake system in reserve for emergencies.

Mr. R. Livingstone: Having regard to the great care which has been taken by the author in the preparation of his facts, it is gratifying to note that main-line electrification is now confirmed as being economically sound. It is natural for those associated with the manufacture of the apparatus required for the electrification of railways to be optimistic in their views on the economies effected, as they are not involved should the financial results be less than expected. At the same time, while this may be the tendency it is a short-sighted policy for any manufacturer to encourage the use of apparatus unless he is convinced that satisfaction will eventually be obtained by his customer and that the line of progress is sound from an engineering and commercial point of view. I fully appreciate the necessity in a paper of this kind of being conservative in one's estimate of the possible saving due to electrification, as in this country we cannot claim to have experience of the work involved in changing over and the cost of running a main-line electrification. We, as manufacturers in this country, have, however, been associated with main-line electrifications in New Zealand, Japan (for the Imperial Government Railway) and France (for the Midi Railway), in addition to which we are at the present time carrying out electrifications in France (Paris–Orleans), Holland (Noord Zuid), Spain (Cataluna), Canada, Japan, Morocco, Southern Railways, G.I.P., and South America (Campos de Jardao). The success of these various electrifications has more than come up to our expectations and, due to a fuller knowledge of the problems associated with main-line electrification, we feel that it is not now necessary to be as conservative in our engineering estimates as would be the case had the experience been confined to work done in this country alone.

Comparative costs.—Reference is made in the paper to the present-day market value of the steam locomotive, and an estimate is given of the cost of replacing these locomotives by electric locomotives. As, however, the railway companies build locomotives only for their own use, their costing system is not one which is used by manufacturing concerns who have to judge their results on all costs which are incurred in manufacture. I am very doubtful whether a modern steam locomotive could be manufactured and sold by a trading concern at a price of £50 to £70 per ton (see page 731). It would appear that the steam locomotives are not debited with a proper proportion of the overhead charges of the railway organization. If, however, it is possible to build a complete steam locomotive at such a low figure as £50 per ton, there is no reason why a figure of £75 per ton should be taken for the electric locomotive structure. I think, however, that the steam locomotive figures are probably on the low side, and that the cost of the electric locomotives are obtained from competitive figures. On checking the figures given for the cost per ton for electric locomotives I find that, although there are slight variations in the make-up, the average cost of the larger electric locomotives is about £130 per ton, i.e. slightly under the figure assumed in the paper. It is possible, of course, to have variations of this figure due to variations in the specification, but the comparisons given in the paper are, at any rate, in favour of the steam locomotive, rather than in favour of the electric locomotive, and still prove an economical case for electrification.

Power of electric locomotives.—The possibility of obtaining large power in proportion to the adhesive weight of an electric locomotive has already been thoroughly established. It may be of interest if I indicate here the amount of power which can be obtained in a motor mounted directly on a locomotive axle. We have built four 3 ft. 6 in. gauge locomotives of the 4–6–0–0–6–4 type for the Imperial Government Railway of Japan, having a total weight of 99 tons and an adhesive weight of 74 tons, on which we have been able to obtain 306 h.p. per motor at the 1-hour rating, i.e. a total h.p. for the locomotive of 1 836. These locomotives give a maximum draw-bar pull of 42 000 lb. and are arranged for double heading. We are also supplying for the Montreal Harbour railway, which is standard gauge at 1 200 volts, locomotives of the 0–4–4–0 type weighing approximately 90 tons with an adhesive weight of 90 tons, on which we are installing four 430-h.p. motors (1-hour rating). This locomotive will give a maximum draw-bar pull of 30 tons taken at one-third of the adhesive weight, but the motors are sufficiently powerful to give a draw-bar pull of 45 tons. Samples of modern electric locomotives are given in Table A as an indication of the maximum draw-bar pull possible.

Additional traffic.—It has been the general experience of railway services that passenger traffic increases after electrification, and, while this might not apply to any large extent to main-line electrifications, it would

TABLE A.

Contract	Type	Gauge	Weight: Total	Weight: Adhesive	One-hour rating	No. of motors per loco.	Total	Tractive effort: Full field	Tractive effort: Shunted field	Gear ratio	Diam. of driving wheel	Line pressure	Max. tractive effort
		ft. in.	tons	tons	h.p.		h.p.	lb.	lb.		in.	volts	lb.
New Zealand	0–4–4–0	3 6	48	48	170	4	680	14 200	—	68/15	$44\frac{7}{8}$	1 500	32 000
Yamanote	0–4–4–0	3 6	60	60	275	4	1 100	20 000	16 000	73/18	49	675	40 000
I.G.R. Freight ..	0–4–4–0	3 6	58	58	306	4	1 224	15 000	12 000	68/23	49	1 500	36 000
I.G.R. Pass.	0–4–4–0	3 6	59	59	306	4	1 224	12 500	10 000	65/26	49	1 500	32 000
I.G.R. Express Pass. ..	4–6–0–0–6–4	3 6	99	74	306	6	1 836	16 500	13 500	65/26	55	1 500	42 000
Montreal Harbour ..	0–4–4–0	4 $8\frac{1}{2}$	90	90	430	4	1 720	42 000	—	85/15	50	2 400	60 000

certainly apply to the suburban portions of these electrifications. Such increased traffic would certainly have a bearing on the minimum economic traffic density for electrification, as shown in Fig. 8. In addition to this, the reduction in many other charges associated with railway working—such as reduced fire insurance, reduced accommodation for rolling stock, etc., together with the fact that the author's estimates are already conservative—would indicate a minimum traffic density of approximately 3 million ton-miles per track-mile per annum as the density at which main-line electrification becomes economical. This figure would cover the majority of the railways given in Table 11.

Mr. J. Dalziel: It cannot, I think, be gainsaid that the author has put forward a sound case for railway electrification. He has the advantage of access to a mass of information not available to everybody, and his knowledge of the subject and his railway experience have enabled him to interpret and to utilize fully this information. That the author's investigations show a more favourable case for electrification from the financial point of view than some of us have hitherto been able to attain is no doubt due in part to the closer estimates that he has been able to take out in the light of the information at his disposal, and in part also perhaps to his being able to put a valuation on advantages which we have hitherto had to pass by. I do not think, however, that he can be accused in any quarter of using figures that he cannot fully substantiate or that railway and electrical engineers generally would not be prepared to accept. That the paper is centred on finance and takes technics largely for granted not only is wise but marks a stage in the literature of electrification. That finance is the core of the whole matter is indisputable. Briefly, the difference between an electric and a steam locomotive, so far as traffic operation is concerned, is that the electric locomotive has behind it the whole capacity of the power station and so can draw therefrom, as and when it requires it, power to a vastly greater extent than is the case with a steam locomotive, the power capacity of which simply finds its limit in the steaming capacity of its boiler. An electric engine, therefore, can take heavier trains and handle them faster, especially up gradients, and can do so without necessarily being heavier than, or even as heavy as, a steam engine. It is now nearly 14 years since in a paper before the Institution of Civil Engineers I showed that an electric engine up the 1 in 90 gradient of the Midland Derby–Manchester line could take a train nearly 40 per cent heavier than the maximum steam train at nearly three times the speed. This illustrates another aspect of electrification and another reason which may in some cases govern its adoption, viz. that of traffic advantage. Apart from the basis of economy on which the author argues, a scheme which offers traffic advantages, or in other words an added facility for doing business, may be adopted for these advantages, and they may exercise a more powerful leverage towards the adoption of electricity for traction than even the promise of fairly substantial economy. Clearly there are certain lines which are approaching, or may before long approach, their limits of traffic-carrying capacity, and on which it will be easier and cheaper to get the required increase of capacity up to

double or more by means of electrification than by putting down additional road bed and tracks, the added electrification capacity coming, of course, from the above-mentioned ability to handle heavier trains at higher speeds. The question of load factor raised in the paper is a very important matter in relation to the costs at which current can be purchased, and I am sure that the paper does not set the railway figures too high; in an analysis which I made of sections of the late Midland Railway I found figures as high and even higher. On a mixed-traffic main line the goods traffic moves mainly overnight, the passenger traffic in the daytime, and there is no dead period as on a suburban line. A four-track line is of course higher in load factor than a two-track line, also the longer the stretch of line dealt with from one power house the higher the load factor; in fact the load factor of a single train could clearly be 100 per cent if the section were long enough. I entirely agree with the author that the full results from electrification cannot be obtained unless steam be completely eliminated on the electric section. If it is retained to even a very small extent a great many services will have to be retained which could be wiped out with full electrification, and these will be increasingly costly in proportion to the work they perform as that work becomes less. The lack of a tender on an electric locomotive is felt only in the one respect of braking; this means in effect that as the tender by its weight helps very appreciably to control the stopping of a train on gradients, its elimination means a reduction in stopping power with an electric locomotive and presents a certain amount of difficulty in respect to the case for the latter. In my own paper already referred to I suggested, as does the present author, the fitting of a power pump in the brake van so that a few of the rear-end vehicles could be controlled by power brakes and so make up for the loss of the tender. In my case I proposed an axle-driven pump and I think that that would perhaps suffice. If so it would be somewhat simpler and cheaper than an electrically driven one with its concomitant apparatus, though it might require a larger reservoir. Referring to the author's remarks on page 748 in regard to track equipment, I should like to ask why, since he must have short lengths of overhead conductors to help his third rail, he does not fully accept overhead conductors which will do all that he requires both on the main line and in sidings without requiring any assistance from a third rail. It seems to me that the proposed auxiliary lengths of overhead conductors with automatically raised and lowered bows will result in a very great amount of breakages of bow gear, expecially at some bridges. In connection with line equipment both of the overhead and third-rail type whether worked at 1 500 or, more especially, 3 000 volts, I should like to ask what drop may properly be accepted on an uninsulated track return. It is a very important point which materially affects substation spacing and the amount and capacity of the return cables to be provided. The 7-volt electrolysis standard does not, of course, enter into the matter outside city areas.

Professor E. W. Marchant: One of the advantages of main-line electrification is the reduction which it effects in unnecessary manual labour. The stoker on the Euston–Liverpool evening train has to shovel in 3½ hours more than 5 tons of coal on to the grate of the fire-box, throwing some of the coal 10 ft. or more. This is a very exhausting operation and automatic stokers are useless. This unnecessary labour would be done away with altogether if electric traction were employed. The author makes no reference to regenerative braking. The amount of saving by regeneration has been discussed at various times and I understand that in some cases it is as high as 10–15 per cent; possibly the gradients on our railway lines are not steep enough to enable it to be used with advantage.

Mr. J. A. Morton: If one accepts the author's axioms then neither the logical argument as built up in the paper, nor his conclusions, can be escaped. One of his principal axioms is that electricity can be assumed to cost 0·4d. per unit. The paper does not state the basis cost of installed plant on which this price is figured. A figure of 8 per cent for interest and depreciation is taken. This appears to be low and should, I think, have an extra 2 per cent added to it for maintenance. The price of coal also seems low at 15s. per ton, especially when account is taken of the coal figures in Table 4. Assuming the generating plant to cost £20 per kW installed, 10 per cent for interest, depreciation and maintenance, and coal at 2 lb. per unit, then in a modern generating station one would expect that current could be generated at 0·4d. per unit, even with coal at, say, 22s. 6d. per ton. If the price of coal were assumed to be 30s. per ton this would become 0·5d. per unit, and I think that the author must have had this figure in his mind as being nearer the mark in view of the 0·5d.-per-unit curves in Fig. 8. To this figure the author adds 50 per cent to cover the loss in transmission from the power station to the wheel of the locomotive (see Table 6), but this is not sufficient because the load factor of the losses is less than the station load factor, as shown by Mr. J. R. Beard * in 1916. With a 50 per cent load factor at the power station, the load factor of the losses would be nearer 35 per cent, and the extra for this would probably be about 0·05d. per unit. In this way one gets a figure of 0·8d. as the cost per unit, as against the 0·6d. taken in column 16 of Table 9. Even allowing for this, however, it can be seen from Table 10 that any traffic density about equal to 3 000 000 trailing ton-miles per track-mile would be a paying proposition. On the other hand, some reductions might, I think, be made in the author's estimates. In connection with Table 9 it seems to me that the transmission line might be worked at 66 000 volts just as well as at 44 000 volts, in which case the losses on this line would be nearly halved. It also appears that £2 000 per mile for the 44 000-volt pole line, exclusive of copper, is much too high, and that £2 000 per mile for the cost of track equipment is on the safe side. This might be cheapened as to siding equipment by using creosoted wood poles and ordinary tramway suspension arrangements instead of catenary suspension. Where necessary these wood poles on sidings can be stayed, as I see no objection

* "Design of High-Pressure Distribution Systems," *Journal I.E.E.*, 1916, vol. 54, p. 125.

to staying along the siding tracks. This would cheapen the siding track equipment very considerably. The proportion of siding tracks is considerable. It also seems to me that for main-line working the distribution pressure might well be raised to 3 000 volts. This would of course mean overhead trolley equipment instead of a mixture of third-rail and overhead equipment, the third rail being omitted altogether. At 1 500 volts the substations would, I suppose, have to be spaced 10 or 12 miles apart, whereas at 3 000 volts they could be spaced two or three times this distance, with a consequent saving. On financial grounds I think that the author's general conclusions are sound. There are, of course, other than financial considerations, some of which are referred to in the appendixes. Amongst others may be mentioned: Less wear and tear of the engineering staff after the electrification is carried out; time saved to the general public in transit (and time is money); cheaper fares and transport and therefore cheaper goods; the electrification would provide work for unemployed men; and our coal supply would be conserved. I suggest that, instead of the railway companies obtaining further net profit as mentioned in item (17) of the summarized conclusions, the fares and transport costs should be reduced.

Mr. W. L. Box: One of the most serious matters is the choice of the line voltage. A decision as regards a standard voltage should be arrived at, as with varying voltages difficulties will arise, especially where main-line and suburban traffic are intermingled. The author refers on page 738 to motors on the South-Western Railway being in service for 7 years without an armature or field coil having to be rewound. As there must have been during this period between 200 and 300 motors in operation, this is an excellent record, and I should like to know if equally successful results have been obtained on the London, Midland and Scottish Railway. On the line with which I am associated some new box-type motors have been in operation for 2½ years and none of these have burned out. On page 738, figures relating to lubrication are given. In this direction we have effected a very great saving in oil consumption by the adoption of the latest type of motors, and the following figures of motor lubrication (including gears) were obtained:—

Old type (oil-ring lubricated) 12·24 pints per 1 000 train-miles (or 0·0229d. per train-mile).
New type (wool- and hair-lubricated) 1·71 pints per 1 000 train-miles (or 0·0032d. per train-mile).

Mr. C. Rettie: On page 748 the author refers to inductive interference with communication circuits caused by high-tension alternating current. In a Report * of the Californian Railway Commission recently published it was pointed out that the main trouble was due to the higher harmonics caused by the operating machinery and that with proper design a good deal of the trouble could be avoided; also that as the telephonic frequency was anything from 200 to 2 000 periods per second, 60 periods or less would have no effect. The Report winds up by stating that "practically all inductive interference to telephone circuits is due to the harmonic currents and voltages, and this renders it important that an effort be made to obtain rotating machinery for use in power systems which produces, as near as is reasonably possible, pure sine-waves of fundamental frequency, and also that an effort be made to obtain transformers and to arrange connections of the same in such a manner as to reduce as far as practicable the distortion of wave-form." With reference to comparative costs, Mr. Thompson of the Westinghouse Co. gives details † of the electric locomotives in use in big stations in New York. The locomotives have two motors each of 2 000 h.p. and the total mileage run per annum is 4 961 628. The cost per locomotive-mile, on a basis of 36 000 miles per annum, is only 3·51 cents, including all charges, the saving in expense in maintenance being equal to about 11 per cent on the cost of the service.

[The author's reply to this discussion will be found on page 774.]

* "Inductive Interference," Railway Commission of the State of California, April 1, 1919.
† *Journal of the Engineers' Club, Philadelphia*, 1916.

NORTH-WESTERN CENTRE, AT MANCHESTER, 18 MARCH, 1924.

Mr. T. Ferguson: I have always been under the impression that the maximum draw-bar pull allowable on British railways is of the order of 13 tons, and I notice that Sir Vincent Raven in a recent paper read before the Institution of Mechanical Engineers in Paris stated that on British railways it is not feasible to go beyond 30 000 lb., and therefore he states that an adhesive weight of from 60 to 65 tons is all that is necessary for an electric locomotive. Presumably this weight is on the basis of an adhesive value of about 500 lb. per ton. The author evidently contemplates much greater draw-bar pulls than this, and makes reference in his tables to a 10-coupled freight engine having 53 000 lb. draw-bar pull, and on page 739 he refers to the combined draw-bar pull of two engines as being between 20 and 25 tons, and states that there is no objection to a single locomotive having a draw-bar pull of this magnitude. There is, of course, comparatively little difficulty in making an electric locomotive either as a single or a coupled unit to produce a draw-bar pull of this magnitude, but evidently some difference of opinion exists as to the desirability of adopting such high draw-bar pulls on British railways, presumably owing to the relatively light draw-bars in use on wagon and passenger stock. Another point in connection with the diagrams of steam and electric locomotives (Fig. 1) is the long, rigid wheel-base proposed for many of these designs. I should be glad if the author would state what he considers to be the limit as regards the rigid wheel-base that will be applicable to main-line railways in this country. The type of locomotive shown as No. 7 in Fig. 1, in which articulated trucks are used, would appear to be the best way of reducing the rigid wheel-base. The author showed on a lantern slide some

details of the side-gear drive, as made by Messrs. Brown, Boveri and Co. In this case the gear wheel lies wholly outside the driving wheels, and the clearance between rail-level and the underside of the gear case is somewhat limited. Will this type of gearing pass through English railway load gauges? The author also refers to the limitation in gear ratio which can be obtained with this type of drive, the limit being imposed by the fact that the motor shaft has to pass over the top of the running-wheel flange with sufficient clearance to admit of the rise and fall of the locomotive frame in the axle-box guides, and at the same time sufficient clearance between the bottom of the gear case and the rail level has to be obtained. The gear ratio is, therefore, obviously limited by the above, as is also the amount of permanent eccentricity, or displacement between the centre line of the gear wheel and the centre line of the running axle, and it is questionable how far this permanent eccentricity can be extended in a new design. The author states that the watt-hours per ton-mile for the various types of trains is not easily determined, and he deduces a figure for this from a series of draw-bar tests made over long runs. It is clear that the area under the curve of draw-bar pull represents the actual work to be done on the trailing load, but how far is the locomotive head-resistance plus its own resistance allowed for? The average value obtained from tests depends partly upon the work done in braking, as well as on the total train resistance, but the latter in a long-distance run is clearly of the most importance and would vary considerably with the speed and also the conditions of wind, dryness or wetness of the rail, etc. If only sufficiently representative train-resistance curves could be obtained from data, then further investigation would be a matter of easy calculation. The question is, whether it is any easier to obtain the watt-hours directly from the draw-bar tests over a given run than to deduce general train-resistance curves from these tests, and I should like to ask the author whether, in his opinion, the train-resistance curves given in Fig. 5 are sufficiently representative to use for future calculations. With reference to the method which he uses for calculating load factor, I note that he adopts as his basis the average power during the hour of maximum demand, and not the maximum power during a much shorter interval, say of 1 or 2 minutes. It is interesting to find how high the load factor is found to be for main-line electric working, and if we compare this with the obviously poor load factors which are obtained on suburban electrifications, where the traffic is largely rush-hour traffic, it would appear to indicate a still further advantage in favour of main-line electrification.

Mr. S. E. Povey: The electrification of main lines on British railways, and in fact the general electrification of railways, is gradually being narrowed down by the several recent investigations which have been carried out by engineers. One main step was made when the Advisory Committee to the Ministry of Transport made a definite recommendation that the standard voltage for the whole of the country should be 1 500 volts d.c. or multiples thereof. Another item is the provision of large power stations in accordance with the 1922 Electricity (Supply) Act. Under this Act the dividing of the country into areas of supply by the various public-supply authorities has practically eliminated the possibility of the railway companies acting as public-supply authorities. It is recognized that the combination of the industrial loads and railway loads is advisable, in order to provide cheap sources of supplies of electrical energy in general. These items may be taken as foundation stones, but I suggest that the author provides limiting values to what might be termed four boundary stones on the question of main-line electrification, the four items being: (1) The necessity of a cheap supply of electricity, (2) cost of electric locomotives and train equipments, (3) costs of operation and repairs, and (4) loading of the sections of a railway. Taking (1), it is of interest to note that although the loads are very peaked and intermittent the plant load-factor of a railway power station can be as high as 95 per cent. The trains work to a definite time-table even when running empty or balancing trips, and no additional trains are run unless definite traffic arrangements are made, and this usually gives ample time to increase the capacity of the plant on load if necessary. Therefore marginal running is not necessary and full advantage can be taken of the overload rating of the plant. The morning and evening rush-hour periods provide the peak loads and are each of about 2 hours' duration. A cheap bulk supply will provide cheap power for the handling of goods traffic in goods yards and therefore enable work in general to be speeded up. As regards (2), it is necessary, as the author points out, to standardize designs of electrical equipments and control equipments to enable them to be manufactured in bulk. It should be possible to standardize the control equipments for both locomotive and motor-car work. The provision of electric locomotives and train equipments from the renewal funds appears to bring the problem of electrification within practical politics, but it must be recognized that the costs of locomotives and train equipments must balance the steam-locomotive costs. It is true that an electric locomotive is capable of working at least double the mileage per day that a steam locomotive can do, but even by reorganizing the working of a railway it is not possible to take full advantage of this. The possibility of electrical equipments operating 23 hours out of 24 can be taken as established. There are cases of electrical equipments on suburban services operating 10 to 20 days in traffic and running 260 miles in a 19-hour day making one stop per mile without interim examination. These suburban services are much more severe than anything one can expect on main lines. Therefore, for express running with stations 20 miles apart and workings covering 24 hours per day, mileages of 500 to 750 are, as far as the equipments are concerned, easily attainable. As regards (3), it is only by standard and tried-out equipments that the above mileages and the necessarily low costs of maintenance can be obtained. Very small details and innumerable designs of contacts and screws should be eliminated. The density of traffic on the whole railway under consideration is shown to be higher than on the present successful suburban electrifications, and the development of Table 10 showing the economy of electrical operation over steam operation is very valuable.

The author somewhat minimizes his method of investigating the question, but by taking the statistics published by the Ministry of Transport he has included the costs of running-shed charges, preparing of locomotives, standing time, etc., which it is otherwise impossible to evaluate. Electrification will provide other large sources of revenue in addition to those indicated by the author. The elimination of smoke and noise makes it possible for the whole of the sites, including the lines approaching the terminal stations and stations in large cities, to be covered by buildings used for hotels, offices and other purposes. Again, goods yards and sidings form a big item as far as land is concerned in the middle of most large cities, and electrification makes it possible to cover the whole of these sidings and goods yards with warehouses and offices. In addition, property in the neighbourhood of the railways will increase in value.

Major P. B. Coulston : The author says, at the top of page 730 : " The decision whether or not to electrify portions of the British main lines will rest with financiers rather than with technical experts." With that view, I think, we shall all heartily concur, because the paper makes it perfectly clear that there is no proposition of any nature whatsoever from the engineering standpoint which the engineers of this country will not be glad to undertake. Finance is, however, a question which engineers will have to consider very seriously. The author does not say how the money is going to be raised, but some figures which I have taken from the *Investors' Chronicle* of 5 January, 1924, are significant. In 1913 the total issues were £196 537 000, of which £52 436 000 represented Government borrowings and the remainder private enterprise. For the year 1923 the total was £271 392 500, of which £173 407 000 was on the Government account and the remainder for private enterprise. That shows that there is plenty of money in this country. We may certainly take it that that 100 millions was invested with the laudable desire that it should be returned with interest, and I think that few prospectuses issued in recent years would show the same safe security with prospects of a reasonable dividend as the proposition put before us in the paper. Roughly 20 years ago a paper was given by Sir John Aspinall, then the chief engineer of the Lancashire and Yorkshire Railway Co., on the electrification of the Liverpool and Southport line, in which he stated the hopes of himself and those associated with him—amongst them the author of the present paper—as to what might be anticipated as the results of electrification. Reading that early paper in conjunction with the present one, I was much impressed with the fact that those intelligent anticipations have been realized. One point which struck me very forcibly was that electrification might have a very important bearing upon the housing of the population. Nowadays high-class residential property is being built as close to electric railways as possible, as they cause none of the inconveniences which are inseparable from steam railways. With the advent of main-line electrification the building of private houses in the immediate vicinity of the railway may be carried out to a large extent.

Mr. J. R. Billington : I can vouch for the accuracy of the dynamometer-car figures which the author has so ingeniously used, together with other railway statistics, to prove his contentions.

Mr. W. J. Medlyn : It is necessary that we should bear in mind that the primary function of a railway is transport, and, quite rightly, the author has given first consideration to the important question of transport economics in dealing with the alternatives of steam and electric haulage respectively. It must not be overlooked, however, that the telegraph and telephone services also play an important part in the organization and control of the transport operations, and, whatever system of electric supply is adopted, it will always be necessary to take reasonable precautions to ensure the continuity and reliability of these communication services. The author recognizes the importance of this aspect in his brief reference to the subject on page 748. The Post Office is also directly concerned in this question of interference from power-supply circuits. Many thousands of pounds have been sunk by the Post Office in the provision of telegraph and telephone circuits carried on the railway undertakings, and in many cases maintained by the railway companies themselves; therefore, in dealing with the economics of railway electrification, it is necessary to keep in mind the effect which the methods adopted may have on the efficient working of the telegraph and telephone plant, whether it belongs to the railway company or to other administrations. In the abstract sense, of course, it does not much matter whether the losses due to depreciation of the communication services are borne by the railway companies or by the telegraph and telephone administrations, because in the long run the cost of wastage has to be borne by the community, but in the particular sense it is only a matter of equity that the party deriving economic advantage from the change of system should also bear the cost of the consequent losses to other parties. In the early days of development, railway engineers appear to have shown a preference for the single-phase system of electrification. The disastrous effect of this system on neighbouring telegraph and telephone wires was fully emphasized in the recent discussion on " The Electrification of the French Midi Railway." * The system has the further defect that high voltages are induced in adjacent telegraph and telephone wires, thus introducing a risk to life and a liability to other damage. It is interesting to note, therefore, that modern practice tends towards the adoption of a less dangerous system. On page 739 the calculations are based upon a three-phase supply converted to 1 500 volts (d.c.). Presumably the adoption of this standard would involve considerable scrapping or modification of the plant now in use on sections of railway which have already been electrified, such as, for example, the Manchester–Bury line which is operated at 1 200 volts (d.c.). On page 748 it is mentioned that the use of cables for the distribution of current would render the cost prohibitive. I understand that on the Liverpool–Southport line an armoured cable was used for supply purposes, but that it rapidly deteriorated owing to the electrolytic effect of the direct current which reached it from the operation of the service; and, as a result, the power-supply wires were diverted to the

* *Journal I.E.E.*, 1924, vol. 62, p. 213.

overhead system. It would, I think, be useful if the author would give us some information on this point, because if supply cables are liable to rapid electrolytic action there is not only the higher capital cost to be provided for but also the extra cost of maintenance and renewals. This question of electrolytic trouble arising from the d.c. system was mentioned by Dr. Parker Smith in his recent lecture on "Railway Electrification in Foreign Countries." * I mention the point because I think it is a matter of very great interest in connection with the economics of electrification. As an illustration of the penetrating inductive effect of this power-supply system, it may be of interest to mention that the Post Office has a lead-covered telephone cable in an iron pipe laid alongside the Liverpool–Southport railway, between the outskirts of Liverpool and Formby. One might naturally expect that the iron pipe and lead sheath would form an effective screen against the inductive effects from the overhead power system, but a very distinct hum is noticeable when one is listening on the telephone line, although in practice this does not generally cause appreciable interference with the transmission of speech. On page 748 the author suggests that the transmission line should not be taken along the railway but should approach the substation by an independent route. From one point of view this idea is attractive, but difficulties are likely to arise in practice in securing such routes, especially where main lines passing through long stretches of open country are involved. In this connection Post Office engineers are liable to feel rather apprehensive regarding the safety of the existing extensive network of Post Office lines generally. At one time it was the practice in America to intermingle telephone wires and power wires on the same poles, including routes along the public thoroughfares. I have recently heard that this practice has now been altered, the power wires being placed on the top arms and the telephone wires below. Before this change was made, on an average every year 24 telephone linemen were killed, whereas at the present time the fatal cases amounted to only six a year. One would naturally expect trouble if we had so many as six cases a year in this country, and the fact that such cases are rare with us is a good tribute to the efficiency with which the electric supply undertakings are constructed and maintained.

Mr. R. Brooks: I do not propose to deal with the broader financial aspects of the paper, but there are one or two control points mentioned by the author which I think are worthy of some discussion. On page 748, in discussing the track equipment and speaking about the necessity for both third-rail and overhead collectors, he says: "As the overhead collector must be clear above the structure gauge, the bow in its 'up' position fouls the structure gauge, and means will therefore have to be provided whereby the bow automatically rises to meet any stretch of overhead trolley and automatically falls when it leaves it, or, alternatively, every over-bridge and tunnel will have to be equipped with a dummy trolley." I take it that he is putting that forward as a problem for design engineers. Dealing with the first alternative, I am in general agreement with the author's statement of the case, except that I do not see the necessity for the automatic raising of the trolley as it approaches an overhead section, if means are provided whereby the collector can be safely raised at any reasonable distance in advance and maintained in that position until it comes on to the contact wire, without doing away with the automatic lowering feature when it leaves the wire. The problem has indeed been studied along those lines, and a gear has been devised, manufactured and put into use, which accomplishes these requirements. The central feature of the equipment is a special control valve which is used for operating a pantograph, or other type of collector, which is air-operated. This valve is of the piston type; that is to say, the valves are actually operated by a piston which is controlled in its movements by two small electrically-operated needle valves, one of which controls the upward movement of the pantograph and the other the downward movement. They are of a type which only requires excitation momentarily. That is a very important point because it very considerably simplifies the problem of automatic lowering. Once the valve is in either the upward or downward position it remains there independent of the continuance or otherwise of the excitation. With regard to automatic lowering, there are probably several ways in which that can be done, but in this particular case it has been effected by attaching special contacts to the pantograph so that when it exceeds its maximum operating height by a very short distance, say 2 or 3 inches, it excites the lowering mechanism of the pantograph, the valve brings the pantograph down, and it stays down until such time as it is raised by deliberate action of the motorman. The approach to any section of overhead wire will have a long, easy ramp, and with this type of control the man can, by holding the control switch over in the "upward" position, raise the pantograph before it reaches the overhead wire, and maintain it in that position until he is under the wire, when he can let the switch go. The pantograph will then remain in contact until on running off at the end of the section it automatically lowers itself. The second alternative mentioned in the paper, namely the dummy trolley, certainly seems to me to have serious disadvantages. In the first place it will be very expensive, especially in congested areas; secondly, a normal type of collector, which is necessarily a very lightly-built structure, is subject to rather severe strain when running for long periods at high speeds without being in contact with the wire. I think that trouble would be developed there. There is also a point to which the author has made a passing reference, namely that there would be considerable insulation trouble with a dummy trolley under bridges and in tunnels. On page 749 the problem of one-man operation is mentioned. No one will deny the accuracy of the statement that it is an extremely difficult problem to attack. It is obvious that the normal type of "dead man's handle" which is used on suburban trains will be entirely unsuited for main-line traffic where long stretches of line are travelled without a stop. No man can be asked to exert a continuous muscular effort, however slight, over extended periods, especially where, as in the gear now in use, the release of the mechanism is instantaneous and there is no time-

* *Journal I.E.E.*, 1924, vol. 62, p. 317.

lag in the operation. It may be of interest to many to know that a type has been introduced which will probably go some way towards the solution of the problem, and is used on one of the Swiss railways. On certain one-man trains the " dead man's handle " equipment is operated by the driving wheels and operates on a distance basis, so that it acts more quickly at high than at low speeds. Moreover, in order to enable the man to leave the driver's position to take off side signals, there is a second button on the other side of the cab to which the man has ample time to go before the gear will operate. He can put his hand on that, and lean out of the window to take any observation he may require. Now although that goes some way it is by no means a solution of the problem; I merely put it forward as a suggestion of the lines on which investigation may be carried out. It seems to me that the author is correct in suggesting that the force of public opinion will for a long time militate against the adoption of a one-man system, however complete or perfect the mechanical safeguards may be. In conclusion I should like to stress the necessity for adhering as far as possible to the simplest form of equipment that will attain the object aimed at. It is extremely easy with electrical equipment to provide all sorts of unusual devices, so that there is a temptation, which it is hard to resist, to demand these things. When mechanical engineers characterize the electric (in contrast with the steam) locomotive as an " appalling box of tricks " they are comparing things with totally different characteristics. On the American lines where a considerable amount of heavy electrification has been carried out, experience has very definitely shown the desirability of eliminating as far as possible every complex piece of apparatus which can be done without, and of adhering entirely to apparatus which is robust and simple in its characteristics and functions. This ideal of simplicity seems to me to be a perfectly attainable objective and I feel certain that the day is not very far distant when the electric locomotives which will be available for all purposes will leave nothing to be desired, in regard to both simplicity and reliability.

Mr. T. E. Herbert: It is rather regrettable that the paper is a reasoned statement of the case for the electrification of main lines instead of an account of a *fait accompli* such as that relating to the French Midi Railway. It is indeed unfortunate that so few engineers attain positions of supreme importance on the directorate, since their experience and training would be of inestimable value in assisting to arrive at a correct economic decision.

Mr. H. Allcock: I agree with a previous speaker in the discussion that the author's most significant sentence is that in which he states: " The essence of the problem is financial, and the decision whether or not to electrify portions of the British main lines will rest with financiers rather than with technical experts." The real difficulty appears to be that the capital cost of the new electrical equipment must be added to the capital cost at which the existing steam equipment already stands in the company's books, so that, until the latter could be written off, the undertaking would be, in effect, saddled with the burden of double capital charges. Ways and means of reducing this burden must therefore be found, and on these grounds, if on no other, I think that the electrical engineers of our railways must contemplate the purchase of current from outside sources, wherever it is available at reasonable prices, instead of building their own generating stations. The case in favour of suburban electrification seems to have been made good in spite of the capital charges, and there may even be special lengths of main line where the growing density of traffic would justify capital expenditure upon electrification as an alternative to incurring the cost of widening the existing road. I should expect that—for instance, on the main Manchester–London (Midland) route—the cost of widening the viaducts and tunnels in Derbyshire would be greater than that of the electrification of the existing track, in which case the electrification of this section of the main line will fall due when the point of steam-traffic saturation is reached. It would be interesting to know the percentage of extra traffic which these metals would carry if they were electrified. This capital question is so obviously the crux of the whole problem that I suggest that the Institution should take advantage of every legitimate opportunity to bring before the Government the justification for financial assistance by the State—under the Trades Facilities Act—for a term of these double-capital years until the financial burden of electrification could be shouldered, unaided, by the railway companies themselves. Not only would the national interests be served by the provision of improved transport facilities, but British technical men would thus be given opportunities of employment in their own industry instead of being forced, through unemployment, either to become unskilled roadmakers at home or to transfer their capital values to some other country offering more favourable opportunities for their advancement.

[The author's reply to this discussion will be found on page 774.]

South Midland Centre, at Birmingham, 2 April, 1924.

Mr. J. Dalziel: Previous speakers have rather reflected on the enterprise of British railways in respect to electrification, but I think that there is a great deal to be said on the railway side of the matter. I hope that the author will be able to drive home the conclusions at which he has arrived, equally effectively in the higher quarters where the future of electrification in this country will be decided. I think that it must be agreed that to have undertaken a very heavy expenditure on a more or less uncertain project such as main-line electrification must be (to the lay mind at least, whatever it is to our own), is not a procedure that in these days could commend itself to railway directors or, if to them, to the shareholders to whom they are responsible. Again, it is all very well to point out, as previous speakers have done, that Continental

and American progress in electrification is ahead of our own, and that the mileage of Continental railways under electrification exceeds the total mileage of British railways. That may be so, but it does not affect the matter. The conditions are different. Whereas our coal is still comparatively cheap, in the countries in which electrification is going on so extensively coal is dear and mainly purchased abroad, and water power is available. The price of coal in Italy, for example, rose at one time to as high as £5 per ton, or even more, with the result that the Italian railways are nearly all being electrified. The same applies to Switzerland, where the railways are undergoing wholesale conversion. In France the southern railways, which are in much the same position, are being electrified. It will be noticed, however, that the Nord railway is not being electrified, for the very good reason that it runs through a colliery area and its coal, like our own, is comparatively accessible and cheap. The matter of economy, in fact, largely turns on coal, and I hope that it is clear that the author's comparison of coal versus current is not a comparison of locomotive against power-station coal, but one of steam-locomotive coal as against all current costs. If we take a comparison of fuel against fuel alone, electric operation gains both because the quantity consumed is less and because a lower quality is used. At the end of the paper the author shows that the saving in fuel is about 50 per cent and, in addition, while locomotive coal must be of the highest grade (say 23s. per ton), electric power station coal may be of the lowest (say 4s. per ton). There is clearly a great economy in this direction, but up to the present it has not appeared to be sufficient to pay for the capital cost of electrification, especially when the other costs incidental to the generation of current are added. The paper shows, however, that the savings to be effected in other directions will compensate for these. There are three directions in which the case for electrification can be bettered, and in one of these, especially, members of this Institution can help materially. The first and most important is to reduce the cost of the apparatus required by the railways. It is for manufacturers to do their part, as well as for the railways to do theirs, and that is the direction in which they can best do it. Another direction is to raise the price of coal, but I hope that this will not be done. Nevertheless, the higher the price of coal the greater the saving and the better the case for electrification, especially as the price of the higher grades used on steam locomotives is liable to rise more than that of the lower grades used for electric generation. The other direction in which electrification may be hastened lies in the realization of its advantages by the traffic-operating officers. The gist of the whole matter in this direction lies in the fact that by the use of an electric engine of weight equal to that of the maximum steam locomotive permitted on the line the maximum train weight on, say, a 1 in 100 incline can be raised by 50 per cent and the speed to something like 3 times. This results, as the paper makes clear, from the fact of the electric locomotive having behind it the whole capacity of the power station, that is to say each electric locomotive can draw upon and use effectively a far greater reserve of power when it requires it to go up a gradient, or for other reasons, than can the steam locomotive which has only its own boiler to draw upon. Another advantage of the electric engine is that it is always ready for work and is not affected by weather variations to anything like the extent that the steam locomotive is. The steam locomotive, in fact, may be slow in responding if the particular quality of coal with which it is being fed does not suit it, while if the weather is cold and the axle boxes therefore stiff it runs more slowly, whereas the electric engine simply increases slightly its power input and output. I have a great deal of sympathy with the desire for a pressure of 3 000 volts. The major portion of my own experience with traction has been with a 6 600-volt single-phase system. There is one difficulty which affects both 1 500 and 3 000 volts, but the latter especially, and that is the drop in the track return. If this can be unlimited, substation distances can be increased as one would expect them to be, though this is not quite as the square of the voltage, but if the track-return drop is to be kept down to a low figure and an equal value throughout, the gain from 3 000 volts against 1 500 cannot be fully realized. The efficiency would rise, but capital expenditure would not be reduced nor would substation distances be proportionately increased. So far as the use of single-phase current is concerned, I should like to make the position clearer. Technically, I do not think that there is very much difference between a single-phase 25-period supply and a d.c. supply. Costs generally would probably show very little difference, though from my own experience I think that d.c. motors must always be somewhat more robust and must always have an appreciable advantage in regard to brush wear and similar details. But the whole question turns mainly on interference with communication circuits, and in this respect the railways in this country, and especially the northern railways, are in an entirely different position from any of the other railways which have used single-phase current for their electrification. The communication circuits on the northern lines are of the utmost importance and they carry, for example, the main Post Office trunk telephones between London and the large northern cities. I think that it is sufficiently clear that any interference with these must be avoided, and single-phase traction certainly does interfere with them to such an extent as to make them unworkable. It has been said that the Brighton line used single-phase current without trouble of this kind, but what the Brighton company did was to put underground all its message circuits within the influence of its single-phase current, and in other cases they have been removed to at least 200 yards from the traction lines. It is fairly obvious that the latter cannot be done in this country. There has been a great deal of rather ill-informed talk, especially at the time of the great storm in 1916, as to why the railways do not put message wires underground and so on. The fact is, of course, that a cabled telephone line, owing to its high capacity, will not work if it is of considerable length, and has to be loaded with inductance coils to counterbalance its capacity at short intervals to enable it to be used at all. I do not say there are no workable underground tele-

phone lines, but they are only workable because they are loaded with inductance. Not only are they very expensive, but I do not believe that even so loaded they give as good speaking-service as is obtainable from overhead lines. I do not say that it is not possible to make message wires workable in the vicinity of a single-phase traction system; for example, the return current can be brought back overhead as close as possible to the outgoing current, so partly balancing its electromagnetic induction, and earthed screening wires can be put between the traction and the message wires to check electrostatic induction, and there are many other devices. All these remedies add to the cost of the single-phase system, however, and if this system makes itself uncommercial because of the cost of remedying the interference with message wires, then there can be no justifiable case for it. Interference with message circuits by three-phase overhead lines is, of course, an entirely different matter. I do not mean to say that there is no risk of inductive effects with three-phase current, but in the single-phase traction system the overhead conductor is in the air in a position fixed by that of the rails; the return current flows along the rail and may in fact take through the earth a different route altogether, so that there is no counter-balance to the inductive effect of the overhead current and the conditions are as bad as they can be. With three-phase power lines the position of the wires is much less inflexible and if they are placed in correct relation to each other and revolved as they should be, and if the message circuits are also revolved, an inductive electromagnetic and electrostatic balance is more or less obtained. The risk of inductive trouble will chiefly arise with unbalanced phases, and this trouble is always liable to occur when lighting or other single-phase supplies are given.

Mr. A. M. Taylor: I wish to dissociate myself from any suspicion of having an undue bias for single-phase work, and although I believe that the adoption of high voltages for single-phase work would carry very distinct financial advantages with it, yet I realize the importance of electrical engineers in this country being practically of one mind on the advantages of electrification, and I shall therefore not discuss single-phase electrification. I have, however, a very strong misgiving as to the advisability of using 1 500 volts as the distribution voltage for d.c. main-line electrification. In order to deal with the question independently, I have worked out the question of traffic service between London and Birmingham, a distance of 108 miles, and have taken a service of 30 passenger trains each way per day of 12 hours—twice the frequency now obtaining—and a service by night of 15 goods trains each way for 12 hours. I am aware that in taking these figures I have neglected the goods service during the daytime, but it somewhat simplifies the case, and, moreover, the passenger service is probably over-estimated, so that this will compensate for the other. On this basis I make the figures to be 2 800 000 train-miles per annum with 12 trains on the line at any period of the day and with a headway of 18 miles between each pair of trains. I have assumed each train to absorb 1 500 kW, i.e. 3 000 kW per pair of trains. I have also assumed a 9-mile spacing of the substations and a distributing copper cross-section of 1 sq. in. on each pole (equivalent to 6 sq. in. if of iron), which allows a current density of 1 000 amperes per sq. in., and I have worked out under these conditions what happens during the cycle while two pairs of trains are changing place on the line. I found that, roughly, the average drop in the d.c. distribution amounted to 16 per cent. If the author had taken a 12-mile spacing the drop would have been of the order of 20 per cent. I note, however, that in Table 6 the author has only taken a 10 per cent drop in the distributing system, and I therefore conclude that in order to bolster up his case he has been forced to use a double copper section, at a cost of another £170 000 or so. This, therefore, is debitable to the use of 1 500 volts. Again, the use of 1 500 volts limits the spacing of the substations to 12 miles, but the proper spacing should evidently be 18 miles. Now it is clear that each substation must be able to deal for a time with two trains simultaneously passing it and hence must have a capacity of 3 000 kW. Nine stations, each of 3 000 kW, gives a total of 27 000 kW, whereas the ideal way would be to use six substations, each of 3 000 kW, giving a total of 18 000 kW, which might be obtained if 3 000 volts instead of 1 500 volts were employed for local distribution, and in addition the 2 sq. in. of copper already alluded to could probably be saved. The author has apparently taken £10 per kW of maximum demand at each substation and so obtained £270 000 as the outlay on the substations. I would suggest, however, that unless he contemplates using rectifiers it would be likely to take more nearly £15 per kW, which, of course, brings his figure up to £405 000 and would make his estimate appear to be £135 000 too low. If, on the other hand, his substations were spaced 18 miles apart the total cost would be £180 000 if taken at £10 per kW, or £270 000 if taken at £15 per kW, so that in the latter case he is spending unnecessarily £135 000 on the substations, plus £170 000 on distributing copper, a total of £305 000. This could largely be avoided by using 3 000 volts as the distributing pressure. In addition to this the wages for, and cost of running, the additional substations would have to be considered. There is, therefore, in my opinion, a clear case for the employment of 3 000 volts. As regards the question of transmission of the power from the generating station, I have looked into this question and, assuming power to be fed from each end of the line, as, for example, from London and Birmingham, I find that the section of the overhead conductors put forward by the author would be only just sufficient if the two parallel lines were both employed, and if one broke down the drop would be serious. Now I believe that 40 000–60 000 volts is altogether too small a pressure to be employed for such a purpose and that the overhead system is not one that should be adopted. On the question of pressure, it was an argument used by some of the advocates of d.c. equipment (see *Engineer*, 1924, vol. 137, p. 342) that three-phase current at 50 periods could be supplied for general purposes from the various substations to smaller towns on the route. If, however, this is to be done, a power factor of the order

of 0·8 will have to be faced instead of a unity power factor, which has been taken in the present case; in fact the present case is unworkable unless a power factor of unity is assumed, and even then the drop is normally of the order of 10 per cent. If, however, the power factor of 0·8 had been assumed, the drop would immediately be doubled and under breakdown conditions would be 40 per cent. Now the regulation obtainable at the substations under such conditions will be totally impracticable for the public supply of electricity and I feel very strongly that the right thing to do is to put in a transmission with underground cables at the highest possible voltage; and I am in the position to prove that assuming, for example, that the "hexaphase" system, which I have advocated, were put down of a capacity several times that necessary for the railway, power could be fed from either end of the line for general distribution purposes on a large scale to towns en route, or right through from London to Birmingham, or vice versa. The interest and depreciation on such a line would be very much less than on the overhead system at an equal voltage; in fact it will only be of the order of 0·001d. per unit with a 20 per cent load factor. The transmission loss from, say, London to Birmingham, or vice versa, will have to be added to this, but it need not be of the order of more than 0·02d. per unit for the same outlay, and this can in fact be reduced to 0·01d. by increasing the copper section at an extra capital charge of only 0·001d. per unit. The result will be a means for linking up large power stations with a north-and-south trunk line, capable of giving power at cheap rates along the route and developing the resources of the country. For example, if power in London were to cost 0·45d. per unit and in Birmingham were to cost 0·42d. per unit, there will be a clear gain, with a liberal margin in hand, in transmitting power from Birmingham to London. In fact a difference of only 0·02d. per unit in the price as between Birmingham and London will amply warrant the free interchange of current from one to the other. It is worth mentioning that the interest and depreciation charges on the line for the amount of power mentioned above will alone be of the order of £113 000 per annum, but this will be paid by the companies or municipalities utilizing the line. It is true that these figures are based on my "hexaphase" system, but even supposing that nothing better than single-phase cables were available and that the limits which are now in serious contemplation in America in connection with single-phase cables were found to be satisfactory, the results will only be reduced by some 30–40 per cent and will still be well worth considering. As regards the use of overhead lines, I feel certain that, if reasonably suitable voltages were to be employed, the distance apart of the conductors will cause serious danger of interference with the Post Office telephone system; and, moreover, there is always the danger of total interruption of both lines (which, I understand, are to be run on one set of poles only) by a stroke of lightning or by collision with an aeroplane. The difficulty with overhead lines on a length of system such as is being considered is that if we confine ourselves to comparatively low pressures of 40 000 or 60 000 volts, the line is inadequate for transmission at anything but unity power factor, and that only in small amounts of power. If, on the other hand, we adopt higher voltages and larger powers (still with overhead transmission) there are the increased inductive effects on telephone circuits, due to the wider spacing of the conductors, and the impracticability of running these overhead systems through many densely-populated parts. There is also the very serious question of accumulation of sleet on the lines and insulators—particularly in the North of England. Speaking generally, I think that the overhead system is unsuitable for such service in this country, except in the sense of a pioneer line to demonstrate the other advantages of electric traction, and even in this case it should be superseded at the earliest possible moment by underground cables. If it should be pleaded that the difficulties of induction and accommodation for the overhead system could be avoided by running the overhead system on a route separate from that of the railway, I can only say that the cost of obtaining wayleaves would be very serious indeed. Moreover, there would be no ready access to the overhead line for the purpose of repair and renewal of insulators, such as there would be if it were situated along the route of the railway.

Dr. C. C. Garrard: It seems to me that the question of the electrification of main-line railways in this country has got beyond the technical stage and now requires more of a political treatment. The author has shown, once more, the great advantages which will accrue from the electrification of our railways, but we have known this all the time; the trouble is to get the railway companies to take action. It is necessary to point out that railway electrification is making rapid strides on the Continent. This is the case not only where water power is available, as in mountainous districts, but also in industrial and agricultural countries like our own, with power derived from steam power stations. Statistics are now available from such electrifications, carried out since the war, showing that the savings effected by electrification have been equal to a return of 15 per cent on the capital involved in the electrification. When considering electrification the auxiliary advantages must not be lost sight of. Take, for example, the city of Birmingham. The centre of Birmingham is most congested, there being no land available for necessary new buildings. Nevertheless, the land occupied by New-street Station represents many acres. If the railway were electrified, the whole of this area could be covered in, and the new hotels and other buildings which Birmingham so urgently needs could be built. The capital value thus created would be extremely large, and would be a set-off against the cost of electrification. It is also useless to wait, before electrifying, to decide upon the best system. We have the single-phase a.c. system and the d.c. system. Both these have been thoroughly proved and, as far as we can tell at present, their relative advantages are approximately equal. The slight advantage which one might have over the other could only be determined after, perhaps, 20 years of trial. We in this country should go ahead with both of these systems. For example, there is the London, Brighton and South

Coast Railway which it was proposed to electrify completely on the single-phase system before the war; this should go ahead. Then at the other end of the country we have the Newcastle–York line of the North-Eastern Railway. The electrification of this on the d.c. system should also go ahead. If these two schemes were to be set going forthwith, as they could be, they would bring most valuable experience which would help in the further electrification of railways. The general public must be made to understand the great advantages that they can get in better service, quicker journeys, and improved amenities generally. They must then bring pressure to bear upon Parliament. It was hoped that the recent railway amalgamations would have helped to bring forward electrification, but at present they seem to have had the opposite effect and the inertia seems to be greater than ever. The electrical profession and industry must, therefore, turn their attention to the general public and secure their co-operation and agitation until the Government forces the hands of the railway companies and makes them go forward without further delay.

Mr. J. D. Carlmark: The estimate of a 33⅓ per cent reduction in favour of electric traction under the item of "Engine-men's wages" in Table 3 appears to be too low; a much larger reduction ought to be possible under electrification. A very important point arising out of railway electrification is the possible supply of current to districts not yet in possession of electric power and the means of lessening the cost where supply already exists. Apart from this it would also increase the demand for motors and domestic apparatus, and this would help the industry to reduce the cost of their goods. The cost of shunting work in connection with sidings, goods yards, sheds, etc., seems to constitute a comparatively large proportion of steam railway expenses. With electricity for disposal along the line, a large amount of this could be saved by the installation of electric capstans where a locomotive is required perhaps only occasionally. Here the power would be at hand when it was required, the cost of overhead conductors or third rail would be avoided, and the expensive locomotive with its attendant motor men would be released for other work. That no armature or field coil has had to be rewound during 7 years' service on two lines speaks very well for the sound construction of the present-day traction motor.

Mr. E. Blakemore (*communicated*): The first page of the paper explains the great difficulty of obtaining a reasonable basis for argument, and lays the blame on the English method of recording railway statistics. The author quotes four bases, viz. number of locomotives per mile of track, coal consumption per mile of track, ton-miles and engine-miles, and rightly states that the last "though a concrete fact, has a somewhat indefinite meaning." It would seem almost impossible to set out a really logical and convincing argument even if statistics were compiled in such a manner as to provide a more satisfactory unit, as main-line electric service and main-line steam service are so totally different in character. In other words, generalization must form the greater part of the argument and the two services cannot properly be compared, because although one starts with the same time-table it would change rapidly due to increased speed on up grades and the decreased gross weight of the train, or, on the other hand, slightly increased trailing weight, and many other advantages now candidly admitted by engineers who have hitherto been sceptical. Despite the difficulties, the paper shows: (i) The feasibility of main-line electrification; (ii) the vital considerations; and (iii) the possibility of many traffic economies. An important point arising from the paper is the effect upon the economic density of an alteration in the cost of coal. Assuming that at 0·4d. per kWh the coal costs 0·15d., then at the tread of the electric locomotive the coal will cost 0·225d. per kWh, i.e. $(0 \cdot 6/0 \cdot 4) \times 0 \cdot 15 = 0 \cdot 225$. Thus coal will cost 2·16d.

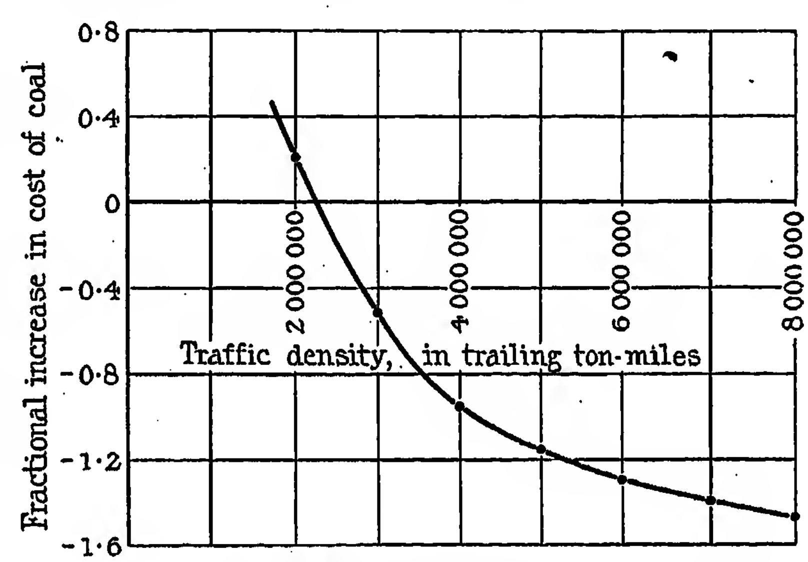

FIG. A.—Curve showing effect of alteration in cost of coal on the economic traffic density.

per electric engine-mile, while it will cost 7·4d. per steam engine-mile. We may therefore write:—

$$\text{Total cost per steam engine-mile} = F + 7 \cdot 4K$$

where K is the fractional increase in the cost of coal.

$$\text{Total cost per electric engine-mile} = E + 2 \cdot 16K$$

$$\text{These costs will be equal when } K = \frac{E - F}{5 \cdot 24}$$

Values of F are given in column 6 (Table 10), and values of E in column 5. Obtaining values of K from this formula and plotting we get the curve shown in Fig. A which indicates that, assuming all other factors to remain constant, if the cost of coal is increased it will pay to electrify most of the lines given in Table 2, but if the cost is decreased there is a greater likelihood of loss unless the traffic density increases. With regard to Table 1, I find it difficult to agree on the method of allocating the charges given as repairs, but I nevertheless regard it as being a very fair comparison.

Mr. R. H. Rawll (*communicated*): The author states that the cost of replacement of steam locomotives by electric locomotives should be chargeable to revenue, on the grounds that railway companies set aside a fixed sum annually for locomotive renewals. Now it appears fairly evident that if it were decided to electrify a particular section of a given line, such a section would,

of necessity, be of considerable length, since, as the author points out, main-line electrification has either to be done on a large scale or not at all. This being so, it is conceivable that the initial cost of a sufficient number of electric locomotives to operate in the new electrified section might be vastly in excess of the normal expenditure on steam-locomotive renewals in this particular district, and thus might easily become a capital charge. It might, of course, be argued that the steam locomotives would still continue in service on the electrified section and that, as their turn came to be replaced, they would be superseded by electric locomotives. This would take a fairly long time to accomplish, however, and considerable loss would be involved in working the two systems of locomotives at the same time over the same section of line, besides delaying unnecessarily the decided advantages which electrification claims. I should therefore be glad if the author could throw some light on this aspect of the question. In ascertaining the probable load factor to be expected, reference is made in the paper to the suburban electrifications of the London, Midland and Scottish Railway, where tests were made with the batteries eliminated at the substations, in order to see what effect this had upon the load factor. A few years ago I was present at one of the above company's power houses while such a test was being carried out. The coal consumption was practically the same as when the batteries were in commission and, as the author has stated, the load factor was slightly reduced. The one outstanding effect was, however, the very increased instantaneous load-kicks on the generating units. The real value of a battery for main-line railway work appears to be in its function of smoothing-out the heavy demands for energy on the e.h.t. system, when, for example, two trains simultaneously start in close proximity to a substation. It has been thought by some that the battery is employed solely to act as a stand-by in the case of an interruption of the supply system. How remote this contingency is to-day is shown by the fact that the substations feeding the underground railways of London do not include a battery in their equipment. But the above smoothing-out action of a battery would not have a marked effect in this case, since the traffic is very much denser than that which would be obtained on a main line, and, consequently, there is more of a constant load on the system.

Lieut.-Colonel H. E. O'Brien (*in reply*) : I was for many years a sceptic as to both the desirability and the possibilities of financial success of main-line electrification; my conversion to other views has been brought about entirely by the new facts which have emerged during the last five years. The extraordinary progress made in electric locomotive design, as witnessed by locomotives recently constructed by British, American and Swiss manufacturers; the data showing the reduction in the cost of repairs and shed maintenance when compared with steam locomotives as communicated by Sir Vincent Raven and others and confirmed by the results obtained on suburban railways; the multiplication of highly economical power stations in the congested areas most suitable for electrification; and the definite indication of very high traffic densities on main-line routes given by British railway statistics, are all factors which have only recently become applicable on a sound basis to the solution of the problem. If one-man operation of locomotives and the cheap electrification of sidings can be put, in the next few years, on an equally sound basis, the case for the electrification of a considerable proportion of the main lines of this country will be irresistible. It is scarcely to be expected that these new data, which have as yet but lightly impressed themselves on the minds of the technical staffs of the railways, will have penetrated to the traffic officers, accountants and directorates, but, fortunately, there will be in Europe within a year or less, and within easy reach of this country, working examples of the new conditions produced by electrification on railways more analogous to British railways than the electrified railways of the United States have been. It is to be hoped, therefore, that both directors and operating officers will be tempted to visit the French, Swiss and Dutch electrifications in the near future and thus obtain first-hand evidence of the improvement that can be effected by the introduction of electric traction on main lines.

Mr. Gill has misapprehended the nature of the change brought about by main-line electrification. If 100 electric locomotives were required to take the place of 100 steam locomotives his calculations would be correct, but in fact only 50, and possibly fewer, electric locomotives are required to replace the 100 steam locomotives. The railway company must maintain their assets—in this case haulage power—intact; this they do by the provision of 50 electric locomotives with the same haulage power in ton-miles per annum as the 100 steam locomotives displaced. Further, the 100 steam locomotives selected for displacement will not be 15 years old but 40 years old, so that their whole value is available in the depreciation fund for the purchase of the 50 or 40 electric locomotives which displace them. In effect, the renewal fund is merely diverted from the purchase of steam locomotives to the purchase of electric locomotives of equal haulage power in ton-miles per day.

It is very pleasant to receive from such an authority as Mr. Welbourn so many figures confirming the conclusions in the paper. The Chicago, Milwaukee and St. Paul Railway is, of course, a special case, but though the cost of haulage on its heavy gradients was favourable to electrification, its low density of traffic was equally unfavourable.

In further support of the claims of economy put forward for electric traction, the following comparison between the cost of electric locomotive operation per train-mile on the recently electrified section of the Paulista Railway and the cost of steam-locomotive operation per train-mile on the same section of line immediately prior to electrification, shown in Table B, is interesting.

It is based substantially on figures published by Dr. F. de Monlwade, General Inspector of the Company,* the figures being reproduced here without alteration except those representing the cost of coal and current, which have been adjusted, as described below, to make them applicable to the conditions obtaining in this country. Owing to the high cost of coal in Brazil the actual saving effected by electrification has been very great indeed, the cost per train-mile before and after the change-over being 69·92 cents (coal 51·14 cents) and 22·97 cents (current 11·97 cents) respectively. In order to make these figures representative of conditions in Britain the author has adjusted the cost of coal to bear the same ratio to the remaining steam-locomotive operation costs that it bears in British practice. The cost of current has been based on the density of traffic which, from the published figures, the author estimates at 3 770 000 trailing ton-miles per track-mile per annum.

TABLE B.

	Cost of locomotive operation on Paulista Railway. Cents per train-mile		Cost of locomotive operation in Britain. Pence per engine-mile	
	Steam	Electric	Steam	Electric (estimated)
Superintendence	—	—	0·54d.	0·54d.
Coal	7·38 c.	—	7·40d.	—
Current, including all charges	—	14·0 c.	—	13·10d.
Wages: enginemen's	6·38 c.	4·08 c.	7·50d.	5·00d.
Repairs	9·67 c.	2·81 c.	6·91d.	2·30d.
Lubricants and miscellaneous	2·16 c.	2·28 c.	1·23d.	0·44d.
Other wages at sheds	0·57 c.	0·34 c.	2·66d.	0·62d.
Total	26·16 c.	23·51 c.	26·24d.	22·00d.

SUMMARY.

Actual saving on Paulista Railway on cost of locomotive operation, using regeneration .. 67·2 per cent
Estimated saving on locomotive operation with coal and current adjusted to British conditions without regeneration .. .. 10·1 per cent

At this density the cost per engine-mile from Table 9 is 13·1 pence in Britain, the ratio between this and the remaining costs being 13·1 : 8·9, which has been used to determine a comparative cost in cents per engine-mile in Brazil. The adjustment in this case is one of increase in cost. In the above alterations to figures the cost per engine-mile and per train-mile are assumed to bear the same ratio to each other in the two countries.

Mr. Taylor emphasizes an objection, raised also by several other speakers, to the proposal to use low-tension distribution at 1 500 volts rather than at 3 000 volts, and, whilst I appreciate the superiority of the latter system in some respects, I do not wish to enter into the arguments for and against the various systems of electrification but rather to demonstrate the advantages of electric traction over steam traction. With this idea in view the system adopted for the purposes of the paper was that which was unanimously recommended by the Electric Railway Advisory Committee as being the most suitable for this country.

Mr. Taylor's further remarks are based on a misapprehension both as to the probable industrial demand on an electrified route and as to the probable length of transmissions required. In the first place, 90 per cent of the industrial load is already concentrated in the near vicinity of the large power stations already in being or under construction; secondly, at least on the West Coast and in the Midlands large and economical power stations are so plentiful in the vicinity of the main lines of railway that practically no transmission line for railway purposes would exceed 30 miles in length. With 12 miles between substations and such short transmission lines the distance between main generating stations will be 72 miles. From London to Crewe is 159 miles, to Birmingham 113, to Preston 209, to Carlisle 300, so that a comparatively small number of power stations would serve the whole London, Midland and Scottish Railway south of Carlisle if electrified. In this connection it may be pointed out that the transmission voltage would not exceed 33 000, and that, as experience has already proved, no difficulty would be experienced in finding routes across country for such transmissions which would avoid all interference with Post Office communication circuits. Central Scotland, the North-East Coast and Lancashire are already covered with such lines. Notwithstanding their greater cost, such independent routes, readily approachable by road, are certainly preferable to those following the railways themselves, the difficulties attending the use of which, viz. liability to interference with communication circuits and difficulty of access

* *General Electric Review*, 1924, vol. 27, p. 312; and *Revista Brasileira de Engenharia*, October 1923.

TABLE C.

Statistical Particulars of the Four Principal Railway Companies in Great Britain, for Year 1923.

Company	No. of locomotives	Mileage reduced to single track: Running lines	Mileage reduced to single track: Sidings	Mileage reduced to single track: Total	Mileage reduced to single track: Sidings, per cent of total	No. of locomotives per track-mile: Excluding sidings	No. of locomotives per track-mile: Including sidings	Engine mileage (incl. electric) in relation to companies' expenditure: With trains loaded and empty	Per cent of total	Shunting	Other	Total	Loaded and empty train-miles per track-mile (excl. sidings)	Engine-miles per track-mile (incl. electric): Excluding sidings	Engine-miles per track-mile (incl. electric): Including sidings	Total engine mileage (steam service only)	Steam engine-miles per locomotive
		miles	miles	miles	per cent			miles	per cent	miles	miles	miles	miles	miles	miles	miles	miles
Southern	2 258	4 179	1 214	5 393	22·5	0·540	0·419	48 912 377	77	9 475 175	5 313 650	63 701 202	11 700	15 200	11 800	57 499 945	25 500
Great Western..	3 944	6 299	2 332	8 631	27·0	0·627	0·457	62 749 639	66	24 552 893	7 765 510	95 068 042	9 970	15 100	11 000	94 938 096	24 000
London, Midland and Scottish	10 292	14 036	6 033	20 069	30·1	0·732	0·513	146 666 590	66	49 679 137	27 218 815	223 564 542	10 400	15 900	11 100	220 952 840	20 720
London and North-Eastern ..	7 398	11 789	5 242	17 031	30·8	0·628	0·434	104 508 802	65	40 039 776	15 417 112	159 965 690	8 880	13 600	9 390	165 427 365	22 400

Company	Cost of maintenance and complete renewals including electric: Total	Per engine-mile, steam and electric	Cost of repairs and partial renewals including electric: Total	Per engine-mile, steam and electric	Running expenses, steam services only: Fuel: Total	Fuel: Per steam engine-mile	Wages: Total	Wages: Per steam engine-mile	Other: Total	Other: Per steam engine-mile	Total: Total	Total: Per steam engine-mile	Total cost of operation: Total includes electrical repairs and partial renewals	Total cost of operation: Per steam engine-mile
	£	d.	£	d.	£	d.	£	d.	£	d.	£	d.	£	d.
Southern	1 172 049	4·42	1 135 477	4·28	1 906 474	7·9	2 053 104	8·55	289 045	1·21	4 248 623	17·66	5 384 100	23·94
Great Western..	2 220 113	5·62	2 043 309	5·17	2 416 843	6·12	3 607 966	9·12	481 017	1·22	6 505 826	16·46	8 549 135	21·63
London, Midland and Scottish	5 710 721	6·12	5 358 985	5·76	6 215 457	6·75	8 422 240	9·14	1 348 339	1·47	15 986 036	17·36	21 345 021	23·12
London and North-Eastern ..	4 249 666	6·37	3 734 089	5·67	4 707 485	6·85	6 457 901	9·38	1 072 008	1·56	12 237 394	17·79	16 021 483	23·46

in the case of a breakdown, are much more serious than Mr. Taylor appears to believe.

Mr. Livingstone doubts whether a modern steam locomotive could be sold by a trading concern at £50 to £70 per ton. The figure of £50 per ton refers to the weight in working order, and £70 per ton to the weight empty, i.e. without coal and water; these are to-day's market prices for two-cylinder non-superheater engines; the cost of three- or four-cylinder engines with superheaters would be somewhat higher. In giving the cost of electric locomotives in Appendix 2 the cost per ton of the locomotive structure is rather too high and that for the control rather too low. He is correct in assuming that the maximum draw-bar pull of an electric locomotive may be taken as one-third of the adhesive weight. The further particulars he gives of typical electric locomotives are interesting, but it must be realized that to make these figures intelligible to the non-technical railwayman, or to the railway mechanical engineer, it is necessary to state the loads that can be dealt with on various gradients and on the level, at various speeds. He refers to certain advantages of electric traction such as reduced fire insurance, reduced accommodation for rolling stock, etc., not mentioned by the author. I desired, however, to make a most conservative statement of the advantages of main-line electrification that would bear the closest scrutiny, and therefore confined myself strictly to those items of locomotive operation which could be evaluated in cash.

Mr. Dalziel's remarks are so much to the point and so valuable that they require no further emphasis by me. As regards the comparative merits of collection from third rail and from an overhead conductor, the outstanding merits of the third rail are the ease with which it can be maintained by the platelaying staff and the ease with which it can be laid without interference with traffic. These, and these only, are the reasons which influenced me in recommending it for the bulk of main-line electrification. There must, however, be no prejudice in the matter, and detailed examination of a particular problem may lead to a decision to use overhead collection exclusively. There is one other point that Mr. Dalziel raises which requires some comment, namely, the permissible drop in the return. It is important to distinguish between maximum momentary drop and the average drop. With 1 500-volt substations 12 miles apart and the worst probable conditions on a double-track main line, the momentary drop in the positive conductor would be 185 volts and in the return 235 volts with third rails of 105 lb. per yard, and the average drop would be much less, probably about 10 per cent.

The use of regenerative braking mentioned by Prof. Marchant is, as he surmises, not of any great importance in this country on account of the absence of steep grades of considerable length.

Mr. Morton questions the figure of 15s. per ton for coal used at generating stations, but this is very representative of the price paid by many large undertakings in this country.* The costs of steam-locomotive coal quoted in Table 4 are, of course, for a quality of coal much superior to that used in most power stations. With regard to the figure of 0·6d. per unit used, stated as the cost of equivalent electrical energy at the wheel of the locomotive, this depends solely upon the cost of generation and the average overall efficiency of transmission given in Table 6, the load factors of the power station and the losses having no bearing on the question except in so far as the cost of generation and the overall efficiency are themselves dependent on them. In using a 44 000-volt system as the basis in calculating transmission costs in Table 9 I have in mind the fact that the power delivered by any one power station to a main-line route will not in general be sufficiently great to justify the use of much higher voltages.

I cannot contribute to Mr. Highfield's belief that electrification will not be adopted solely because it will reduce working expenses. This fact is, indeed, the most important argument in its favour, and if electrification is not done primarily with a view to increasing net profits it will never be done. Two at least of the other factors which in Mr. Highfield's opinion offer more decisive arguments for electrification,

TABLE D.

Typical Costs of Coal Delivered to Generating Stations, for Year 1923.

The average calorific value of the coal is 10 900 B.Th.U. per lb.

Distance from London	Pit-head price per ton	Miles hauled from colliery	Carriage on railway at ½d. per ton-mile	Handling and trimmers' wages at generating station	Total cost
Miles	s. d.	Miles	s. d.	s. d.	s. d.
7½	10 11	92	3 10	1 0	15 9
187	11 4	11	5½	2 4	14 1½
211	11 5	26	1 1	1 7	14 1
Averages	11 3	43	1 9½	1 8	14 8

* See Table D.

viz. the possibility of increasing train loads and speeds, and in other countries the desire to make use of water-power resources, are ultimately reducible to statements of diminished working expenses.

In reply to Mr. Jackson's inquiry concerning the engine-mile basis used in Tables 1 and 3, for the steam railways in all cases the gross engine-mileage has been used which, as he suggests, is a basis favourable to steam traction in the comparisons.

The choice of route for transmission lines mentioned by Mr. Carter has been considered in the reply to Mr. Taylor's remarks on the same subject. The figure used in the paper for the cost of track equipment, viz. £2 500 per track-mile, does not include an allowance for the removal of signal rods, etc. The last column in Table 5 is an estimate based upon an actual case. With regard to my estimate of 92 per cent for the average efficiency of transformation, this figure may be anticipated with substations equipped with mercury-arc rectifiers. The average for a typical suburban system having rotary converters has been found to be 90 per cent, which agrees well with the figure given by Mr. Carter.

In reply to Sir Philip Dawson, whose communication is a valuable contribution to the history of railway electrification, I realize that the presentation of a special case of main-line electrification would have been more convincing. The investigation of a specific case of electrification on a large scale—for to give the most fully successful results such an operation must be on a large scale—is, as Sir Philip Dawson shows, a lengthy business demanding not only the co-operation but also the interest of all the departments on a railway. I felt that under these circumstances a more convincing case could be made by using the average figures for train-miles, traffic densities, costs, etc., and by showing first that electrification would give a moderate net return on the capital expended for the whole of a large railway system, from which it follows that there must be some portions of that system where the traffic density is higher than the average and where the cost of certain services must also be higher than the average, the electrification of which would result in a saving greater than that actually calculated. The trains hauled on such routes are likely to be of the heaviest class, drawn by the largest and most expensive types of steam locomotives, and the cost of repairs and fuel will therefore be higher, probably 25 per cent greater than the average for the whole system. It is interesting to me to find that my estimate of the gross freight and coaching ton-miles of the London, Brighton and South Coast Railway, as deduced from the locomotive coal-consumption per ton-mile, is 2 699 million ton-miles per annum, as compared with Sir Philip Dawson's figure of 2 616 million ton-miles per annum. The cost which he gives of electrifying 500 miles of single track seems to be very high, even allowing for the prices prevailing in 1921, but no doubt a large proportion of the cost was for the additional track facilities required to handle the expected increased traffic, and the whole of the new electric stock has also been included. I am glad to feel that such an authority as Sir Philip Dawson supports me in the view that main-line electrification is a revenue-earning proposition and that it would prove of great value to railways, the engineering industry and the public alike.

The information given by Dr. Garrard as to the return obtained on the capital expended on electrification abroad is most valuable; I only regret that it is not published in full. It seems to be the general experience that at least 15 per cent return on capital may be expected from any electrification where the traffic conditions are favourable. It is regrettable that both Dr. Garrard and Sir Philip Dawson should have revived the old alternating current versus direct current controversy. I feel that the prolonged discussion of their respective merits reveals the fact that the choice of system will have but little effect on the financial success of a main-line electrification. The choice of system to be adopted is rather governed by the *status quo*, the large mileage of existing electrified lines at 600 and 1 200 volts on the direct-current system, the greater suitability of that system for suburban work, and the existence of a very large mileage of suburban railways whose electrification could, and should, be dealt with at the same time as that of the first main lines to be electrified. If current is purchased, the electrification of 100 miles of four-track route would not cost more than £5 000 per track-mile, or a total of £2 000 000 exclusive of locomotives, which would be the only charge debitable to capital account in carrying out the electrification. Interest and depreciation charges on this sum would not exceed £160 000 per annum, equivalent to about 5d. per engine-mile on a basis of 8 000 000 engine-miles per annum. Such a large-scale experiment could not possibly result in any loss to the company carrying it out, the capital expended would represent about 0·15 per cent of the total capital of the British railways, and the experiment would result in the whole controversy as to whether main-line electrification would be profitable or not in this country being concluded for ever, one way or the other.

Mr. Carlmark touches on a subject which would require a paper to itself when he raises the question of the most economical method of carrying out shunting work on an electrified main line. The relative merits of electrifying the sidings and of using accumulator locomotives, and the extent to which capstans could be used, would require the most careful investigation—and the case of each station would have to be decided on its merits. He is on less-debatable ground when he refers to the low cost of maintenance of the modern traction motor. The advances made in the design of traction motors and of electric locomotives in recent years form the basis of the arguments presented in the present paper and cannot be over-emphasized, as a large part of the economy to be effected by electrification arises from the reduction in maintenance costs both in the works and at the locomotive sheds.

Mr. Blakemore also makes an important point when he draws attention to the effect of the rising cost of coal. Nobody doubts that coal costs will tend to rise rather than fall, and that the least improvement in the internal trade of this country would result in a substantial rise in coal prices.

Mr. Rawll's point about the replacement of the

steam locomotives is akin to that made by Mr. Gill, but his supposition that the capital cost of the electric locomotives required to operate some portion of a system might be greater than the normal expenditure on steam-locomotive renewals for that section is least likely to apply to those sections electrified which would be chosen, as has been stated elsewhere, for their high traffic density, and on which the steam locomotive renewals-cost would be above the average and the possibilities of continuous service of the electric locomotives more nearly realizable. The estimates in Table 9, showing the relation of cost of current per engine-mile to traffic density per track-mile, allowed the very large sum of £12 per kilowatt of substation plant, the cost of a 6 000 kW substation being taken at £72 000, including a large battery. I do not consider that batteries would actually be required for main-line work, but I included them in order to make the estimates conservative and unassailable; with modern plant the contingency of appreciable interruptions to supply is extremely remote.

Mr. Lydall is correct in his assumptions with regard to curves 1 and 3 in Fig. 5. Curve 1 includes machinery resistances, that is the frictional resistance offered by the engine mechanism, in addition to the resistance of the locomotive as a vehicle; it has been derived by Mr. L. H. Fry from the results of a large number of tests on various locomotives but applies only to engines with six wheels coupled.* The machinery resistance of the locomotive at any speed may be taken to be 9 per cent of the tractive effort at the tread of the wheels at that speed. Curve 3 represents only the vehicular resistance of the electric locomotive (see Appendix 4 to paper) and is typical of locomotives having individual drives running on level straight track; it does not apply to locomotives having coupling rods. Very little is known about the average resistance of freight trains and I do not wish to suggest that curve 2 in Fig. 5 is applicable to freight trains in general. The curve has been derived by Mr. Fry from the results of tests made by Sir John Aspinall on four-wheel fully-loaded 10-ton goods wagons having an average tare weight of 6 tons, and it agrees well with some tests recently made by the London, Midland and Scottish Railway. In these latter tests, five in number, freight trains of weights between 800 and 1 250 tons trailing and made up of fully-loaded four-wheel wagons having an average gross weight of 16 tons were hauled a distance of 24½ miles at an average speed of 16 miles per hour.† The average resistance, after making allowance for change in level, was found to be 8 lb. per ton. If allowance is made for the fact that the average maximum speed reached in the tests was 26 m.p.h. it will be found that the agreement with curve 2 is very good. The resistance of freight trains as ordinarily built up, that is composed of mixed four-wheel and bogie wagons often only partly loaded, together with covered vans, must, in thea bsence of better experimental data, be estimated from results such as the above. With regard to the remark that curve 4 in Fig. 5 representing the resistance offered by L.M. and S. Railway passenger stock gives figures which are high in comparison with those obtained in tests on the New York Central Railway, this difference may well be accounted for by differences of weight, type of bogie, etc., between the types of coach experimented with, and I believe that this curve, which has been derived from the results of recent experiments, is fairly representative of modern passenger stock as used in this country. However, in calculating the energy consumption for an electrified main line I purposely used a fairly high figure for the watt-hours per ton-mile in order to ensure that my estimates of saving should be conservative.

In connection with the very interesting figures given by Mr. Lydall in regard to the mileage performed by electric locomotives, I believe that electric freight locomotives on the Midi Railway of France are doing 1 000 miles weekly.

In answer to Mr. Ferguson, it can only be repeated that it is the usual practice on British railways to double-head many trains, the two locomotives then used having usually a combined draw-bar pull of at least 60 000 lb. at starting, and 16 000 to 20 000 lb. when running. The rigid wheel-base of locomotives having driving wheels coupled by side rods should in general not exceed 17 feet, but with electric locomotives having individual axle drivers of the Brown Boveri type, in which side play of the axles may easily be provided for, this restriction does not apply and wheel-bases of 18 to 19 feet may be safely employed if desired. Messrs. Brown, Boveri's side-gear drive will pass through most of the English main-line gauges, and can easily be modified to pass any English main-line gauge. By the courtesy of the Swiss Federal Railways I recently inspected one of these locomotives after over 80 000 miles' running on work quite equal to heavy main-line duty in England; everything about the locomotive, including not only the gears but also the tyres, was in such perfect condition that the most sceptical steam-locomotive engineer or traffic officer would have been convinced that the claim that locomotive repair-costs would be reduced to between one-third and one-fifth those of steam locomotives was justified. With regard to the work done on the train as recorded by the dynamometer chart, this, of course, does not include the work required to propel the locomotive itself, which should be obtained by using curve 1. Further details in connection with this and the other resistance curves have been given in the reply to Mr. Lydall's remarks.

Mr. Povey, Major Coulston and Dr. Garrard all draw attention to the increased use of station sites which could be made on an electrified line owing to the absence of steam and smoke, but it should also be pointed out that in the neighbourhood of London especially and other large towns the reduced accommodation required for locomotive stock would free an appreciable acreage of valuable sites for other purposes. In this connection I again wish to repeat that the case I have endeavoured to make for main-line electrification is based solely on the economies to be effected in connection with locomotive operation and repairs. If the other and consequential advantages are included the case is unanswerable.

Mr. Medlyn need not fear interference with Post

* For this and formulæ for engines with four and eight wheels coupled, see *Engineer*, 1909, vol. 107, p. 310.

† See Table 7.

TABLE E.

Comparison of Locomotives.

Description	Passenger		Passenger		Freight	
	General Electric Co. (U.S.A.) electric locomotive for P.O.R. 1923	Two passenger steam locomotives. Modern British practice	General Electric Co. (U.S.A.) electric locomotive for P.O.R. 1923	One passenger steam locomotive. Modern British practice	Brown Boveri electric locomotive for Italy	Two freight steam locomotives. Modern British practice
Type	4–6–6–4	4–6–0 4–6–0	4–6–6–4	4–6–2	4–8–2	0–6–0 0–6–0
Overall length	62 ft.	120 ft.	62 ft.	70 ft. 5 in.	48 ft.	104 ft.
Total wheel base	53 ft. 6 in.	110 ft.	53 ft. 6 in.	60 ft. 10⅝ in.	38 ft. 9 in.	90 ft. 9 in.
Weight in working order	107 tons	238 tons	107 tons	149 tons	98·4 tons	180 tons
Weight per ft. run overall	1·73 tons	1·98 tons	1·73 tons	2·12 tons	2·05 tons *	1·73 tons
Weight per ft. run wheel-base	2·0 tons	2·16 tons	2·0 tons	2·45 tons	2·54 tons *	1·98 tons
Adhesive weight	75·4 tons	119·0 tons	75·4 tons	60·0 tons	63·0 tons	97·5 tons
Greatest axle load	12·6 tons	20·0 tons	12·6 tons	20·0 tons	16·0 tons	18·0 tons
Weight of electrical and brake equipment	46·0 tons	—	46·0 tons	—	44·4 tons	—
Weight of mechanical portion	61·0 tons	—	61·0 tons	—	54·0 tons	—
H.P. at draw-bar, 1-hr. rating	2 550 h.p.	1 970 h.p.†	2 550 h.p.	1 510 h.p.†	2 350 h.p.	1 540 h.p.†
Draw-bar h.p. per ton	23·8 h.p.	8·28 h.p.	23·8 h.p.	10·1 h.p.	23·9 h.p.	8·57 h.p.
Tractive effort starting	50 700 lb.	58 940 lb.	50 700 lb.	29 840 lb.	35 300 lb.	49 120 lb.
Speed at 1-hr. rating	56 m.p.h.	—	56 m.p.h.	—	31 m.p.h.	—
Draw-bar pull at above speed	17 100 lb.	13 200 lb.	17 100 lb.	10 000 lb.	27 930 lb.	18 600 lb.
Maximum speed	105 m.p.h.	80 m.p.h.	105 m.p.h.	80 m.p.h.	62 m.p.h.	50 m.p.h.
Number of running speeds on controller ..	8	—	8	—	6	—
Weight of passenger train haulable up 1 per cent grade at 56 m.p.h. for 15 mins.	480 tons	220 tons	480 tons	190 tons	—	—
Weight of freight train haulable up 1 per cent grade at 31 m.p.h. for 30 mins.	—	—	—	—	760 tons	430 tons
Maximum speed on level with above train	80 m.p.h.	75 m.p.h.	80 m.p.h.	80 m.p.h.	50 m.p.h.	50 m.p.h.
Weight of passenger train behind draw-bar that can be accelerated at ½ m.p.h. per sec. on 1 per cent grade	480 tons	450 tons ‡	480 tons	220 tons ‡	—	—
Weight of freight train behind draw-bar that can be accelerated at ½ m.p.h. per sec. on 1 per cent grade	—	—	—	—	320 tons	390 tons ‡
Cost of electric locomotive:						
Motors	£7 000	—	£7 000	—	£6 000	—
Control equipment	£6 300	—	£6 300	—	£2 640	—
Mechanical portion at £70 per ton ..	£4 270	—	£4 270	—	£3 780	—
Total	£17 570	—	£17 570	—	£12 420	—
Cost of steam locomotive at £80 per ton of weight empty	—	£17 600	—	£8 800	—	£10 640

* With Brown Boveri individual drive this figure may readily be reduced by extending the wheel-base. † Based on grate area. ‡ For short period only at starting.

Office circuits by power lines; the principles to be observed to avoid such interference are well known. It is undesirable to put lead-covered cables in the near vicinity of electric railways worked on the direct-current system, but jute-served cables, even if laid in the ground, have proved immune.

Mr. Brooks's solution of the problem of raising and lowering the pantograph is very neat; it will, however, be necessary to provide means for preventing the motorman from raising the pantograph until he is actually under the section equipped with the overhead collector wire, otherwise the pantograph might be raised prematurely and come in contact with some structure. For passenger work the provision of any overhead collector would probably be as unnecessary as it is for suburban electrifications. Its necessity arises in connection with freight-train operation and busy sidings where there is much movement of staff. As to one-man operation of main-line locomotives, there is little doubt that when the demand actually arises the technical skill of British engineers is quite capable of providing a control which will satisfy both the Ministry of Transport and the public as to its safety in operation. Every operating engineer will agree with his remarks as to the desirability of robustness and simplicity of design in electrical apparatus for railway work. The electric locomotive is, in fact, a simple piece of apparatus compared with a steam locomotive, owing to the fact that all moving parts have purely rotary motion, that no portion is exposed to high temperatures or large differences of temperature, and that the complicated portion, i.e. the electrical connections, are all permanent and stationary and require practically no maintenance or inspection.

Mr. Allcock should realize that the electrification of even 5 000 track-miles of main line, or about 15 per cent of the total running track-mileage of Great Britain, would only increase the total capital of the railways by about 3 per cent. As he suggests, an extensive electrification scheme of much less magnitude than the above would have a marked effect on the unemployment problem.

Mr. Roger Smith suggests as a basis unit to be adopted for comparison purposes, ton-miles per engine-hour. Some such unit would be more satisfactory than that used in the paper, but its use would have involved a more elaborate statistical research than the time available permitted. I am in complete agreement with Mr. Roger Smith's other remarks and also with Mr. Lydall's. It is improbable, however, that the weight of British trains will tend to increase very much; the weight of the freight trains is limited by their length, which, in turn, is limited by siding accommodation, and in passenger work the tendency is rather towards more frequent trains of less weight.

In conclusion, I venture to add three more tables. Table C gives the principal locomotive operating statistics for 1923 for the four principal companies, as taken from their published accounts. Table D gives the prices of fuel suitable for power-station purposes to compare with that given for locomotive purposes in Table 4 of the paper. Table E is a most striking comparison between recently-built electric locomotives and the nearest comparable steam-locomotive combinations.

SELECTION OF BALL AND ROLLER BEARINGS FOR ELECTRICAL MACHINES.*

By T. D. TREES, Associate Member.

(*Paper first received* 31*st October*, 1923, *and in final form* 3*rd May*, 1924.)

SUMMARY.

The paper has been prepared to indicate the lines on which the selection of bearings should proceed in cases where it has been decided to employ ball or roller bearings for electrical machines.

In order that due allowance may be made for bearings under different conditions of loading, it is suggested that some method should be adopted that would employ definite factors graded according to the service required, by means of which the capacity of bearings could be properly checked when necessary.

It is not sufficient simply to use the makers' tables of safe loads for all purposes, and certain "load factors" are put forward in order to furnish a rational basis of comparison.

In conclusion, observations of a general character are made with regard to capacities, costs, types, etc.

A list of previous papers on the subject is given for reference.

INTRODUCTION.

The use of ball and roller bearings in nearly all classes of machinery has grown considerably in recent years, particularly since the war, and although comparatively few electrical manufacturers used them in standard practice in pre-war days, various firms have now adopted them in their standard machines.

It is not desired to discuss the relative merits of the different types which may be used or the advantages and disadvantages of ball and roller bearings in general, although widely different ideas appear to be held by engineers with regard to their use in electrical machines. There is no doubt that ball and roller bearings offer certain advantages, but there is equally no doubt that their importance is sometimes rather exaggerated, and it is quite an open question whether it is worth while for the manufacturer to embody them as standard in preference to the ordinary ring-lubricated bearings. Some firms compromise by supplying their standard frame sizes with either type, according to the requirements of the customer.

Papers dealing with the design and manufacture of ball and roller bearings have been read by various authorities, but mainly from considerations of interest to the bearing manufacturer or the automobile engineer, and articles of either a theoretical or descriptive nature have appeared in the technical Press from time to time.

The present paper is presented as an attempt to amplify the work above referred to, since it is thought that the mathematical papers and articles on ball bearings published hitherto have been of only a limited value to the machine designer or operating engineer.

The design and manufacture of ball bearings is quite a special subject, and formulæ which may be accepted as being theoretically correct offer little assistance to the practical engineer or the user of these bearings, because such formulæ should only be used in combination with certain constants or allowances which have been derived from the results of tests and experience in actual manufacture. Thus it may be easily understood that the quality of the materials used, the relative proportions of the balls, races and grooves, and the accuracy of workmanship, etc., are all vital factors to be considered. These factors are fully known by the bearing maker only and in practice may differ appreciably as between one firm and another.

It is therefore not proposed to deal with the theoretical side of the subject which has been so ably expounded, but it is felt that some notes on the selection of bearings may prove interesting and helpful.

Although the engineer is not called upon to design the actual bearings it is essential that he should be able to determine whether or not his bearings are capable of sustaining the load imposed. It frequently happens in practice that a motor of standard frame size may be suitable electrically for a certain duty, but would not be reliable if fitted with bearings of the standard size. In such cases it too often occurs that the bearings are taken for granted or are passed as correct by simply checking the catalogue load tables without making any allowance for the nature of the load to be sustained.

GENERAL.

Supposing that it has been decided to use ball or roller bearings, how shall the size or type be determined? The electrical manufacturer, in general, takes the path of least resistance, or, in other words, hands the job over to the bearing maker whose name happens to be best known to him, or the one who is most favoured at the time for some reason or other. This practice has been adhered to, partly because it is so simple, but principally because the bearing makers recommend and encourage it. In some catalogues the load-carrying capacity of the bearings is not stated at all; in others we are told that they are merely comparative figures, so that lack of confidence in the load tables published leads most engineers into accepting the makers' offer to determine the size and type of bearing necessary. Although much may be said for this method of dealing with the question,

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it is not considered to be sound engineering practice, for reasons which will be given later.

Another method that is sometimes used is to fit bearings of the same diameter as the standard ring-lubricated bearings employed on similar machines, without reference to the maker or checking the load capacity in detail. This is not to be recommended; it may be satisfactory in the case of machines which have necessarily very stiff shafts, but the engineer is really working in the dark, and the bearing maker cannot be expected to accept any responsibility if the size thus chosen is not correct.

The chief reason given for adopting the first of these methods is that the ball-bearing maker is a specialist and also one who has acquired much experience in the pursuit of his profession, but it should be realized that this experience has been obtained simply because he has tackled problems of all kinds that have been passed to him from many directions in response to his insistent invitations.

Let us consider for a moment other details of a machine—insulation, for example. The maker of the material gives test figures regarding electric strengths, tensile strengths, etc., but the designer determines the electrical or mechanical loading. Similarly for steels the maker will give the magnetic or mechanical properties, but the engineer decides for himself with what flux density or stress he shall work the material under certain conditions. In the author's opinion it is no more rational to place the bearings out to be designed by another firm than it would be to request the steel maker to design the shaft.

There is no obvious reason why basic load values and allowances should not be assigned to ball and roller bearings of all sizes according to their type and make, by the aid of which the engineer could himself determine the size and type of bearings to employ on the machine, even though his factors of safety or allowances were not similar to those used by the bearing maker. After some experience he would have the great advantage of knowing fairly well what results to expect under almost every condition, and with this end in view the author is putting forward definite recommendations which are based on personal experience and may or may not agree with the practice followed by any bearing maker.

Little or nothing has been published by British bearing makers regarding the allowances that should be made when selecting bearings to meet various requirements, and the engineer is assured that it is not possible to publish tables or charts to indicate the capacity of the bearings under varying conditions. Tables are published giving the maximum steady load which the bearings will stand under continuous running for certain types and sizes. They do not state, however, what life may be expected for a bearing under the load and conditions quoted, nor are the load values guaranteed. This absence of definite information is regrettable, although there are very good reasons from the makers' point of view why all bearing problems should be referred to them. It should not be expected that a motor manufacturer who is making standard machines in large quantities can afford the time and trouble to submit each individual case for the bearing maker to consider, especially as in many instances stock machines are sold and guaranteed without the manufacturer knowing what is the exact nature of the drive and the resultant loads that will be imposed on the bearings. In special cases where a non-standard machine is being designed, suitable bearings can be chosen for the particular duty required, but when considering the selection of bearings for a standard line of motors it is essential to ensure that the shafts and bearings are large enough to withstand the maximum loads which are likely to be imposed upon them under any conditions for which the motors may be designed.

For simplicity of production when manufacturing machines for general purposes it is not desirable or customary to design the bearings for each individual service, and therefore it will frequently happen that the machine is employed for a duty which does not by any means load the bearings to their maximum capacity. For example, there may be steady loads such as are experienced in direct-coupled motor-generator sets in which the drive subjects the shafts to torsion only and the sole function of the bearings is to support the weight of the rotors. On the other hand, a machine may have to withstand severe shocks such as are experienced when driving rolls or crushers through gearing. In each of these cases machines having the same size of frame may be capable of giving the output required, but obviously if the bearings fitted are capable of withstanding the latter duty much lighter bearings could be employed if desired on the machine which is not subjected, by the nature of the drive, to additional external load.

Due to the increased output developed in the case of intermittently rated motors such as those used for crane duty, the bearings are subjected to still heavier loads for machines having the same size of frame. Therefore, if the standard motors are to be suitable for intermittent ratings, it is necessary to provide stiff shafts and bearings of ample capacity when the mechanical design is standardized for each machine. In general, standard motors only have one size of shaft per motor, but it is a matter of policy rather than of design to settle in the first case the purposes for which the machines shall be manufactured. With some firms it is the practice to make a standard line of machines for general duties, but to supply similar machines with stiffer shafts and larger bearings for crane ratings.

Selection.

Assuming that the above general questions have been reviewed and settled, it is now proposed to examine various types of drives which may be used and to suggest comparative methods of determining the load-carrying capacity of the bearings under these conditions.

It is not sufficient simply to calculate the theoretical load and choose a bearing suitable for this capacity from the load tables, without making certain allowances according to the type of drive employed. The theoretical bearing load should be multiplied by some value (which is here called the "load factor") before the bearing size is selected. Although in certain cases it may happen that values given in manufacturers' load tables are far too high, in using the load factors given later

In the paper it is assumed that the load tables published are not too optimistic and that with ordinary good fitting the bearings may be expected to have a reasonable life when running under conditions similar to those on which the tables are based.

Belt drives.—It is considered desirable to draw attention to a few important points regarding the calculations of the belt pull. Although these may appear obvious, it is found that they are frequently overlooked in practice. It should always be borne in mind that the standard formula for the ratio between the tensions on the tight and slack sides respectively is correct only when the belt is on the point of slipping. Sufficient initial tension must be applied in order to ensure that the belt will not slip at the maximum overload of the machine, and this initial tension is usually much greater than that theoretically required to transmit the normal full-load output. At any load less than the maximum overload that the belt will transmit, the tensions on the tight and slack sides will automatically adjust themselves so that the difference in belt tension is equal to the effort required to transmit the lower power, and the total belt pull on the bearing will be the same at all loads if the motor is running at constant speed. In the case of machines which run at variable speeds,

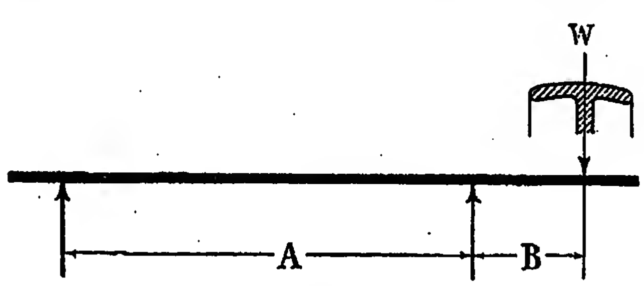

FIG. 1.

however, the bearing load will be rather greater at the low speeds than at the high speeds, because the centrifugal force acting on the belt is less at those speeds, and therefore the belt pressure on the pulley is not relieved to the same extent.

It is interesting to note that if a heavier belt than necessary be fitted a greater centrifugal force has to be counterbalanced at full speed, and consequently a greater initial belt tension is required than would be the case with a lighter belt. Due to the absence of the centrifugal effect at starting, the bearing loads are higher than when running, but it is not considered necessary to make allowance for this fact, as this increased load occurs for a brief period only. In this connection it may be observed that a belt drive is able to transmit a certain amount of torque over and above its full-load torque. This amount depends on the initial belt tension and the final running speed of the machine.

The chief point that it is desired to emphasize is that the pull on the bearing will be practically the same at all outputs of the machine and that it depends primarily on the initial belt tension.

Another fundamental rule is frequently overlooked in practice when the effect of the "leverage" of the shaft when calculating the belt pull on the bearing is neglected. This may mean that the figure thus arrived at may be anything from 10 to 25 per cent too low. For example, in the case shown in Fig. 1, where W = belt pull, A = bearing centres, and B = pulley centre, the actual load on the driving-end bearing due to belt pull is

$$W\left(\frac{A+B}{A}\right)$$

For normal leather-belt drives and for cases in which the angle of drive and the arc of contact, etc., are not known, it may be assumed that the ratio of the belt tensions is $2\cdot5:1$, i.e. the total belt pull is $2\cdot33$ times the effective belt pull.* In addition, as the motor is frequently guaranteed to withstand an overload of 50 per cent momentarily, allowance must be made for this fact in order to ensure that the belt will not slip at the maximum overload, and the initial belt tension should allow, say, a 10 per cent margin.

Taking into account these various factors the total belt pull becomes

$$W = \frac{2\cdot33 \times 1\cdot5 \times 1\cdot1 \times \text{horse-power} \times 33\,000}{V}$$

$$= \frac{3\cdot85 \times \text{horse-power} \times 33\,000}{V}$$

where V = velocity of belt in ft. per min.

For general purposes and for convenience it is proposed to use a round figure and make the "load factor" = 4. Thus

$$\text{Belt pull} = \frac{4 \times \text{horse-power} \times 33\,000}{V}.$$

Gear drives.—In contrast to the load imposed on the bearings by belt drives, the bearing load for a geared drive varies directly with the output of the machine, and in the case of a motor for a varying load the bearing is consequently not always working under the maximum conditions of loading. Although the bearing must be large enough to withstand peak loads, its life should be considerably longer than that of the bearing running continuously under such peak-load conditions as those customary for belt drives. On the other hand, however, some allowance must be made for inaccurate machining of the gear teeth, as although a high standard of precision has been attained in gear-cutting practice one cannot expect to obtain absolutely perfect meshing of the teeth. It is well known that exceedingly high loads may be impressed on the teeth if the gears do not mesh accurately, and it has been stated by one authority† that these impressed loads increase in direct proportion to the square of the tooth velocity.

When designing gearing it is customary to increase the factor of safety by working the teeth at lower stresses at the higher tooth velocities. The arbitrary values of the permissible stresses at various velocities given by Wilfred Lewis‡ have long been adopted as standard and proved satisfactory in practice. Allowance should be made in a somewhat similar manner for the

* In cases where the coefficient of friction and the arc of contact are such that a different value is obtained for this ratio, the load factor should be modified accordingly.

† O. LASCHE: *Zeitschrift des Vereines Deutscher Ingenieure*, 1899, vol. 43, p. 1417. See also DANIEL ADAMSON: "Spur Gearing," *Proceedings of the Institution of Mechanical Engineers*, 1916, Jan.–May, p. 353.

‡ *Proceedings of the Engineers' Club of Philadelphia*, 1893, vol. 10, p. 16. See also DANIEL ADAMSON, *loc. cit.*

probable increase of load imposed on the bearing by tooth pressure as the pitch-line velocity increases.

The curves in Fig. 2 have been drawn to illustrate the author's suggested load factors. For ordinary non-reversing metal spur-gearing, the load factors given by curve A may generally be recommended.

In motors which may be continually reversing, the bearings will probably be subjected to additional shock loads due to "backlash," and it is considered that some higher load factors (as given in curve B) should be assumed when selecting the bearings.

Where the motors are fitted with non-metallic pinions such as paper, raw hide or fabric, it is expected that the shocks will not be so severe, consequently slightly lower load factors may be used, such as those shown in curve C, whilst for double helical gearing a still lower factor may be employed, as much smoother running is obtained, the values suggested in this case being shown by curve D.

In order to avoid confusion, no curves have been shown for reversing-gears of the raw hide or double helical types; but an increased load factor should certainly be allowed for reversing-gear drives similar to that shown by the two curves for spur gears.

For machines which are guaranteed to withstand such an overload as 25 per cent for half an hour, it is of course essential that the gear thrust should be calculated at this overload. For momentary overloads, however, it is not thought necessary to base the capacity of the bearing on the maximum overload, but a somewhat lower factor should be used which may be taken from Fig. 3. The equivalent gear thrust then becomes

$$\frac{k \times l \times P \times 33\,000}{V \times \cos\theta}$$

where P = maximum power (expressed in horse-power) other than momentary overload,
V = tooth velocity at pitch circle in ft. per min.,
θ = pressure angle of gear,
k = load factor from Fig. 2,
l = overload factor from Fig. 3.

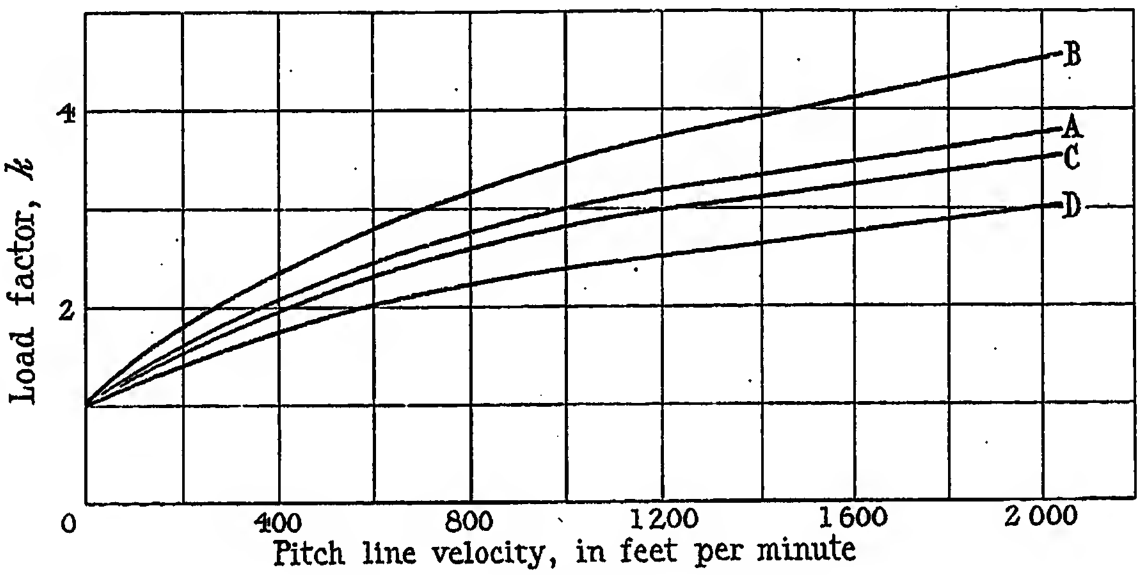

Fig. 2.—Bearing load factors for machine-cut gearing.

In order to make the meaning of this overload factor clear, let us assume two cases :—

(a) 20-h.p. motor capable of developing 100 per cent overload momentarily.

(b) 20-h.p. motor capable of developing 25 per cent overload for ½ hour and capable of developing 100 per cent overload momentarily.

For case (a).—The equivalent bearing load should be taken as that due to 20 × 1·5 (from Fig. 3) = 30 h.p.

For case (b).—The 100 per cent momentary overload is equal to a 60 per cent increase on the maximum half-hour output of 125 per cent.

The constant l, therefore, is now 1·3 (from Fig. 3) and the maximum sustained load of 1·25 should be multiplied by this factor. The equivalent bearing load is thus due to 1·25 × 1·3 × 20 = 32·5 h.p.

Rope drives.—It will generally be found that rope drives are not employed on motors of the smaller outputs such as those in a standard range of sizes fitted with ball or roller bearings, but are more commonly used on the larger machines in which the standard practice is to use lubricated bearings. Although for this reason it may not be necessary for some manufacturers to concern themselves with the loads to be expected, yet other firms will find it desirable to make provision for rope drives in special cases if not in their standard lines.

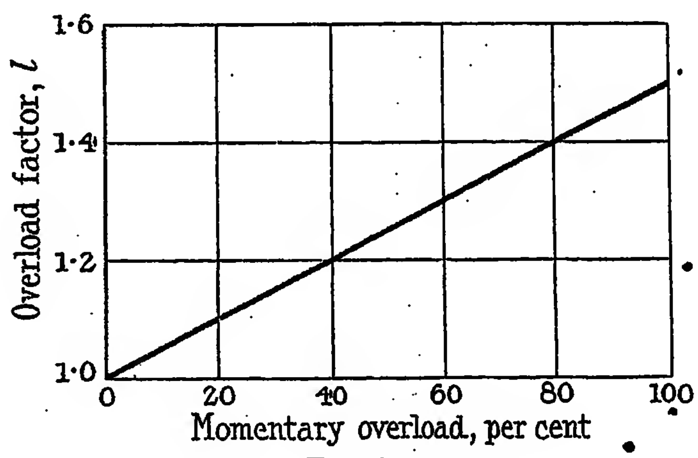

Fig. 3.

Where this type of drive is used, it is to be noted that the conditions regarding initial tension and load being continually on the bearings, etc., are similar to those discussed for machines with belt drives.

The use of grooved pulleys is customary, and by a wedging effect the grooves of standard shape considerably increase the effective value of the coefficient of friction between the ropes and the pulleys. In consequence the tension on the slack side is very much lower than that required for an ordinary belt drive transmitting the same output, the ratio of the tensions being approximately 4 : 1. The corresponding expression for the rope pull then becomes

$$\frac{1{\cdot}66 \times 1{\cdot}5 \times 1{\cdot}1 \times \text{horse-power} \times 33\,000}{V}$$

which simplifies to

$$\frac{2{\cdot}75 \times \text{horse-power} \times 33\,000}{V}$$

Link belts with grooved pulleys.—It is occasionally necessary for machines of moderate output to use leather link belts of tapered width running in grooved pulleys. In such cases, as in ordinary rope drives, the wedging action increases the effective coefficient of friction. Therefore the tension on the slack side and consequently the total load on the bearing is lower than that necessary for belt drives with flat pulleys, and the formula for the belt pull may be taken as

$$\frac{2 \times \text{horse-power} \times 33\,000}{V}$$

the load on the bearing at all outputs being practically equal to the initial tension, as in the usual belt drive.

Chain drives.—Where chain drives are employed for transmitting the power developed, the conditions are more like those obtaining for gears, since no tension is necessary on the slack side of the chain, and the load on the bearing is directly proportional to the output of the machine. However, although there is no slip such as is experienced with belts, and the drive is positive, a considerable amount of flexibility is gained from the working clearances between the links and pins, as a result of which the bearing should not have to withstand anything like the same amount of incremental load due to inequalities of pitch and vibration as a bearing for a gear drive. For these reasons the load factor can be omitted and the load on the sprocket within the usual range of chain speeds (from 500 to 1 300 ft. per min.) may be taken as

$$\frac{P \times 33\,000 \times l}{V} \quad (l \text{ from Fig. 3})$$

In some instances the weight of the chain may appreciably affect the bearing load; this naturally depends on the position of the motor relative to the drive. For the roller chain such as may be used for low speeds up to 50 h.p., the total weight of the chain for average conditions may be approximately equivalent to 10 per cent of the effective chain pull. For the silent chain type generally used for higher speeds the chain weight will vary from about 5 per cent to 20 per cent of the effective chain pull for average drives from 3 to 200 h.p. It will be necessary to make allowances in this respect to meet individual conditions, in the same way that one should include the weight of belt or rope pulleys, flywheels, clutches or gearing, etc., when considering the total bearing load.

Direct coupling.—For direct-coupled machines not subject to such external loads as are described above, it is considered that the bearing should be capable of withstanding under steady running conditions the amounts stated in the makers' load tables. At the same time, however, it is pointed out that considerable loads may be impressed on the bearings unless direct-coupled sets are properly lined up on the same bed-plate. In cases where there is a possibility of the machines getting out of line, flexible couplings should be used, but in this connection it is important to observe that the fitting of a flexible coupling does not obviate the necessity for careful lining up when erecting.

When a unit having several bearings is required, such as a motor-generator set in which two or more machines are connected by solid couplings, it is preferable to have only one thrust bearing fitted for the complete set, as if a thrust bearing is fitted to each machine an initial load may be imposed on these bearings when the couplings are being bolted together. Similarly, if the thrust is to be taken by journal or location bearings, only one bearing in the complete set should be fixed, the remainder being given sufficient end-play in the housings to enable them to take up their correct running position without restraint.

Loads due to miscellaneous causes.—In addition to the specific cases mentioned above, the bearings have to withstand loads due to causes which are frequently lost sight of, and, although it is not proposed to go into details as to what allowance should be made for all cases, it is considered desirable to draw attention to some of these points. For example, when bevel or single helical gears are fitted on the motor shaft a certain axial thrust from the gears has to be sustained by the motor bearings, whilst, when double helical gears are employed, provision should be made for a small end-play, either on the armature shaft or the gear-wheel shaft, in order that the pinion may centre itself with the gear wheel. If this is not done, end thrust will be set up in one or other of the bearings.

The unbalanced magnetic pull due to shaft deflection and bearing wear, which may be present in certain machines, can be determined by well-known methods, but is often neglected when calculating bearing loads. Although it has not the same importance as when ring-lubricated bearings are employed, it should not be ignored.

Some trouble was experienced with certain vertical motor-generators fitted with ball bearings; this was simply due to the fact that the necessity of having shafts just as stiff for vertical as for horizontal machines was not properly understood. Because there was no external drive and the load due to gravity was not acting on the shaft and journal bearings as in horizontal machines, it was apparently assumed that small shafts and bearings could be employed. Such reasoning is unsound, because for high-speed machinery, such as

electric motors, it is necessary to consider the whirling action of the rotor, and in order that the critical speed of the shaft shall not be near to the normal running speed it is essential to provide a shaft of exactly the same stiffness, whether the motor be horizontal or vertical. If the shaft is not stiff enough, vibrations will be set up and, as a result, severe loads may be imposed on the bearings, thus causing trouble for which the bearings are often unjustly blamed.

Another important question is that of the machine fitted with a third bearing. It is a very common practice in these cases to assume that the load from the drive is shared equally between the outer bearing and the bearing at the driving end of the motor, and that the weight of the motor is shared proportionally between the two motor bearings. This method of calculating the bearing loads is quite wrong and may lead to bearing trouble. There are various methods of arriving at the actual load on each bearing, but these need not be discussed here. Generally speaking, the middle bearing may be expected to carry about 70 per cent of the total load due to both the weight of the rotor and the load imposed by the drive. Usually, most of the remainder is carried by the outer bearing because the driving load is much greater than the weight of the rotor, whilst the motor bearing remote from the drive may only be called upon to carry about 3 or 5 per cent of the total load, dependent on the direction in which the driving load is acting in relation to the downward weight of the rotor and the distance between bearing centres. Similarly in the case of direct-coupled motor-generator sets with three bearings, the middle bearing should be capable of supporting probably about five-eighths of the total weight of both rotors, and, unless correct methods be employed for calculating the bearing loads, it is probable that smaller bearings than are necessary may be selected for the centre bearings of both three- and four-bearing sets.

The above remarks are made on the assumption that the shafts are horizontal, but again one must not overlook the effect of incorrect alignment. In practice it is difficult to obtain perfect alignment, and if the outer bearings are higher than the centre bearings the load will be more evenly distributed. Therefore, while it is necessary to make the centre bearings large enough to carry safely the maximum theoretical load (assuming that the bearings are all horizontal) it is also desirable to put in larger outer bearings than appears to be necessary, due to the fact that the bearings will seldom be perfectly in line.

For machines which are intended to operate in tropical climates or in situations where high temperatures are experienced, it may be necessary to reduce the permissible bearing loads. The bearings may be expected to operate satisfactorily, for the loads given in the makers' tables, with suitable load factors such as have been suggested, at temperatures up to about 60° C. In many situations such as engine rooms in India and on board ship in the tropics, the temperature of the bearings may exceed this figure and it is desirable to specify a lubricating grease of a high melting point and also to reduce the permissible loads to, say, 80 per cent of the normal values.

While various questions have now been dealt with in order to provide for the different types of loads which may be imposed, no mention has been made of any factor connected with the duration of service. Obviously, one may expect the bearings of a motor which is run at only infrequent intervals and for short periods to have a much longer life than the bearings of a machine which is running for 24 hours per day and 7 days per week, and in consequence one may say that the bearings in the first case could be run at a much lower margin of safety.

It has been stated that the life of ball bearings varies approximately inversely as the cube of the load carried. Thus, on this basis, the bearings of a machine which is running for only 1 hour per day could carry twice as much load as those of a machine running 8 hours per day, given the same size and life of the bearings. Although this may be usefully considered in special cases, it is not proposed to introduce a "life factor" for general use when selecting bearings for a standard line of machines. It may be said that this point is taken account of more or less automatically by the well-known fact that electrical machines, when running at intermittent or short-time ratings, will give a much higher output for the same temperature-rise than when running continuously, and as the manufacturer naturally wishes to use the same size of bearings whatever the duty, the result generally will be that the intermittently rated machine with heavier loads will have approximately the same bearing life as the continuously running machine with lighter loads. However, for a standard line it is not desirable to assume that for short-time ratings the bearings can safely be expected to carry heavier loads than those suggested by the foregoing load factors. It is not fair to choose small sizes on the assumption that all machines under these conditions have only a very small working life. It is obvious that a motor may be intermittently rated and may still have to run continuously, being on light load most of the time. The bearings, therefore, are not necessarily to be under the same rating conditions as the motor in which they are fitted, and they may also be operating under the same load whether the motor is developing its full output or running light.

General Considerations.

There are many considerations which may influence the choice of bearings, and various observations which may be of interest may now be made. For example, as already stated, although bearings of the same type, size and price, may be purchased from different firms, the loads which may be safely carried by these bearings, according to the makers' tables, vary considerably. This is illustrated by the curves in Fig. 4 plotted from the loads quoted by different British manufacturers. It is interesting to note also that according to general practice the quoted safe load is directly proportional to the square of the shaft diameter. It is rather a striking fact that, taking bearings of, say, 3 inches diameter, the safe load which may be carried varies from 2 000 to 7 700 lb. even from these curves, which do not include heavy-type bearings. The curves have been plotted from the makers' safe loads at 1 000 r.p.m.,

this speed being chosen for the purpose of illustration since it is a common motor speed. For journal bearings it appears to be the general practice among bearing makers to quote such values that the load varies inversely as the cube root of the speed (r.p.m.).

Several formulæ have been published from time to time to give the load capacity of ball and roller bearings, but it is not desirable to take a general formula and apply it to any particular make in the absence of definite information, unless it is recognized that only an approximate result can be obtained. Even when the diameter and number of balls or rollers and the diameter of the ball track are known, there are unknown differences in design and manufacture, clearance and materials, which reduce the value of the average formula. However, if one is dealing regularly with one particular largely by factors apart from the output and speed, and depends on the rotor weight, distance between bearing centres, whether the core is built on a sleeve or not, size of air-gap, etc. It therefore follows that one firm may have shafts of a larger diameter than another for the same outputs, and in cases where the shafts are comparatively large it may not pay to fit medium-type bearings, but for smaller shafts the medium type becomes necessary. If the bearing cost is not important, then for the average machine it is better to fit medium-type bearings, the increase in cost being a smaller percentage than the increase in load capacity obtained, and a reserve capacity is obtained which gives improved reliability for normal drives and entails less departure from standard construction for higher-load conditions in special cases.

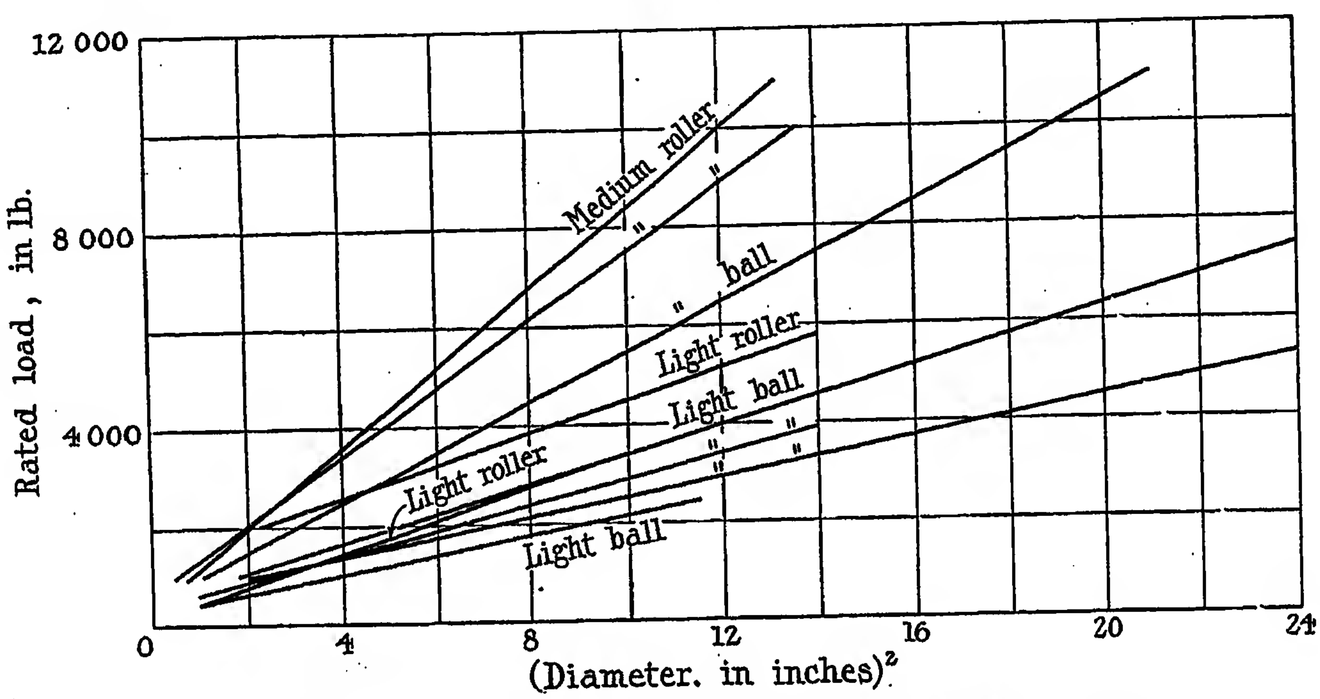

FIG. 4.—Relation between safe load (lb.) and (bearing diameter)^2 at 1 000 r.p.m.

make and type of bearing, and prefers to have a formula, it is easy to see that:—

$$\text{Safe load at 1 000 r.p.m.} = aD^2 + b$$

and $$\text{Safe load at any speed } v = (aD^2 + b)\sqrt[3]{(1\,000/v)}$$

where a and b are constants, D = diameter of bearing, and v is expressed in r.p.m.

This can readily be solved for a and b by plotting from the makers' load table.

It is not proposed to dicuss the heavy types or metric sizes as this would unnecessarily lengthen the paper. The bearings usually employed in electrical machines are the light and medium types which are generally capable of carrying the loads normally experienced.

In the determination of the most suitable journal bearing for a standard line, it is natural that cost should be a deciding factor if reliability and capacity are not thereby affected. It will be found that, load for load, the medium-type bearing is cheaper than the light type in most British makes. The question of type is not, however, merely a question of load and cost; it may probably be determined automatically by the size of shafts required for the construction of the particular machines under review. The shaft size is governed

The diameter of the bearing for the light type is from 1·3 to 1·5 times the diameter necessary for a medium-type bearing of the same capacity, and in some cases where the former has been preferred the bearings are mounted on sleeves or hubs to avoid increasing the shaft diameter. This practice can often be adopted with advantage in vertical machines having a direct-coupled drive.

It may be of interest to compare the capacity and cost of average bearings of given diameters, although, as already pointed out, these are not necessarily the deciding factors. In the curves shown in Fig. 5 the medium-type ball-bearing cost and load have both been taken as unity. It is then clear (if we accept the general statement from the makers that a roller bearing will safely carry 50 per cent more load than the single-row ball bearing of the same make) that the roller bearing is a really good investment for the heavier loads. Naturally, this does not mean that one should fit roller bearings whether there is sufficient work for them to do or not; in cases where they are not necessary it is hardly good business to increase the cost of the machines by fitting roller bearings throughout.

The external dimensions of the roller and ball bearings

of similar types are identical and the methods of mounting are similar except that the outer race of the roller bearing should be clamped stationary. Therefore with very little modification to the bearing housings or caps either type can be fitted, and it is suggested that it may be worth while to consider the fitting of both in a standard line. Provision may be made by suitable machining, so that for light and medium duties ball bearings are used, and for heavy duties roller bearings. Generalizations have been made by one firm regarding the fitting of ball bearings in motors up to a certain horse-power, and roller bearings in motors above this horse-power. It will, however, be apparent from the paper that the selection of the bearing is not merely a question of the horse-power transmitted, and consequently it is not correct to lay down definite rules that are only arbitrary and in practice tend to hamper clear

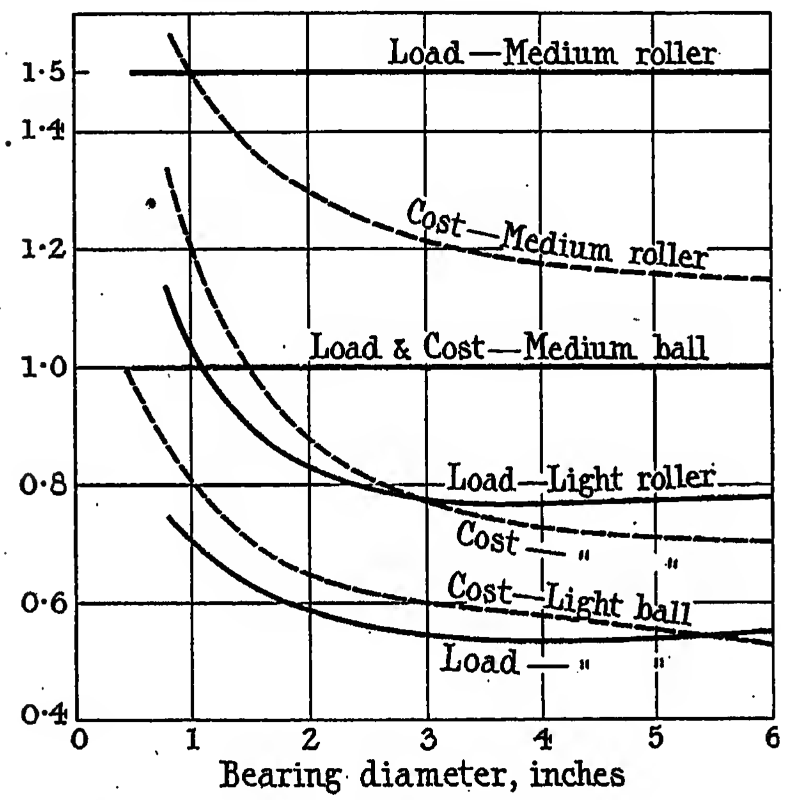

FIG. 5.—Comparative load capacity and cost of average bearings.

thinking. Sweeping statements, such as the above, are apt to be accepted by some engineers without consideration if put forward in an attractive manner, and although it may be safe to follow such rough-and-ready rules it may not be economical or necessary.

With the roller bearing of the short, parallel type which is referred to above, and is in most common use, it is necessary to make provision for supporting the end thrust on the shaft. This may be accomplished by using a radial ball bearing at the commutator or slip-ring end to carry the combined radial and thrust load, or by fitting a separate location bearing, or by means of a thrust bearing in addition to the journals. The last two methods entail an additional cost which need not be incurred in the majority of cases. The bearing remote from the driving end is usually lightly loaded, and a ball bearing can easily be arranged to take the end thrust. In this case it is preferable to use a bearing of the non-filling slot type; although those with filling slots in the ball races may be suitable in general, it is considered that filling slots introduce a weak point into the bearing and render it more liable to failure when running under maximum load conditions.

The following formulæ have been given by various firms for determining the permissible combined radial and thrust load:—

$$W = 3T + R$$
$$W = 4T + R$$
$$W = 6T + R$$
$$W = 7T + R$$
$$W = R + \frac{T}{2 \sin \alpha}$$

(For self-aligning bearings)

$$W = R + (0\cdot0004\,v + 0\cdot8)T$$

(For single-row bearings without filling slot)

$$W = R + (0\cdot0004\,v + 1\cdot4)T$$

(For single-row bearings with filling slot)

where W = equivalent radial load,
R = radial load,
T = thrust load,
α = pressure angle,
v = speed (r.p.m.).

It is considered that general requirements will be met by the use of the expression $W = 3T + R$, but the value of R must include the load factors previously suggested.

In the author's opinion an excellent combination for motors subject to heavy duties is to fit a medium-type parallel roller bearing at the driving end, and a medium-type double-row self-aligning bearing of the same diameter at the other end to support both the radial and thrust loads. If it is desired to fit separate location bearings it may be assumed that the capacity for axial loads is equal to 25 per cent of the rated radial loads. A thrust bearing is very commonly fitted not only for roller bearings but also when ball journals are employed, and it will be found that where these are required it is preferable to purchase them with sleeves ready for mounting direct on the shaft, thus eliminating a possibility of careless adjustment during assembly. Suitable sizes are put forward for both medium- and light-type thrust bearings in Fig. 6.

Taking the medium-type location bearing with an end-thrust capacity assumed equivalent to 25 per cent of the radial load, it is found that the light-type thrust washer of the sizes suggested is cheaper and of equal or greater capacity. Except in extreme cases, however, the author considers that the combined duty of journal and thrust bearing can be sustained successfully by the self-aligning type fitted remote from the driving end in motors up to about 200 h.p.

The leading bearing manufacturers issue publications containing a great deal of information in regard to the applications of their respective products, and it is not desired to include such matter in this paper. No comments will therefore be made on methods of mounting, machining allowances, etc., except to remark that the makers' instructions regarding fitting should be carefully carried out.

It is well known that ball and roller bearings are

splendid examples of the high standard of precision which can be obtained in everyday engineering practice, and it should be noted that this feature is absolutely essential to their proper functioning. It cannot be too strongly emphasized that articles which are made to such fine limits and which receive so much care at every stage of their construction should be accorded a corresponding amount of care from the time of their purchase until they are in actual operation. It is most probable that incorrect machining and fitting has been responsible for many of the troubles experienced, especially with those firms who have not manufactured standard machines with these bearings and in consequence may

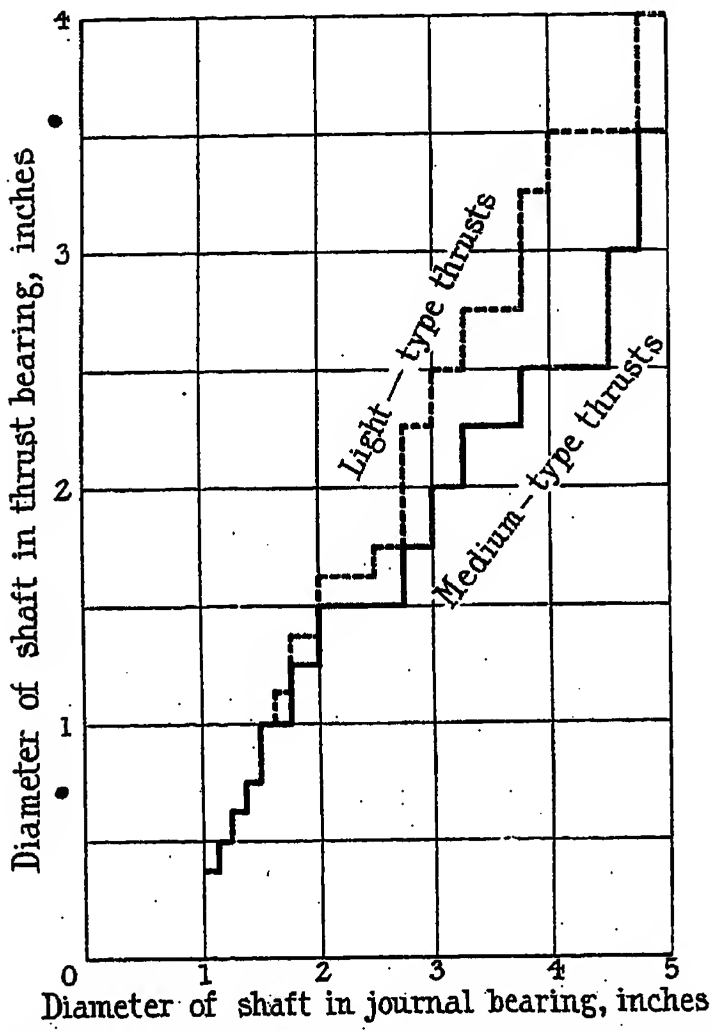

FIG. 6.—Sizes of thrust bearings (with sleeves) for use with medium-type ball or roller bearings.

lack experience in this direction. From such instances mistaken prejudice may easily have arisen against ball bearings in general or against a certain type in particular.

Care should be taken to state definitely that the bearings are intended for use in electrical machinery, in order that the makers may supply bearings of the "slack" type to allow for expansion. The bearings should be inspected on receipt in order to ensure that the correct type has been sent, and then repacked in the makers' wrapping with the original protective grease covering on them. The bearings should on no account be permitted to lie about the stores or on the fitting benches unpacked. It is important that they should be properly protected from picking up dirt or iron filings, etc.

The practice of repairing bearings or building up "new" bearings from old sets is not recommended. The manufacturers have most elaborate systems of gauging and selecting balls, rollers and races in order to obtain the high degree of accuracy necessary. When it is considered that a manufacturer will produce balls which differ by only 0·0001 inch between maximum and minimum, and then will sort these into five different lots for the purpose of assembling all balls in one bearing to within 0·00002 inch of the same size, it may be realized how inefficient the ordinary engineering shop is for this class of work. The amount of clearance, end-play, alignment and eccentricity are all important factors, and attempts to patch up old bearings for use in high-speed machinery should not be entertained.

It has been suggested on various occasions that the sizes of bearings for electrical machines should be standardized according to the output and speed. The operating engineer does not always realize the difficulties of the designer, but there are many good reasons (which may be apparent from the points discussed in the paper) why the designer should be left free to determine his own size and type. The wide differences between the safe loads of various makes and types is one drawback to the standardization of bearing diameters, and the different types and proportions of machine construction for similar outputs is another difficulty.

In the author's opinion it is most undesirable that design details should be taken out of the responsible engineer's control by a standardization committee, and the arbitrary methods usual to standardization should not be recommended in this connection.

Many questions have not been touched upon, such as those affecting the theory and manufacture of the bearings; it was felt that these were rather outside the purpose of the present paper, which has been prepared from the engineer user's point of view as an attempt to put forward helpful information for those interested in the application of these bearings.

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FAITHFUL REPRODUCTION IN RADIO-TELEPHONY.

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Summary.

On account of the great number of processes and transformations that energy undergoes between its acoustical source and the ear of a listener when wireless telephony is the means of transmission, it is not possible in a single paper to explore in detail all the avoidable and unavoidable possibilities of distortion. The proper understanding and application of certain general principles enable individual circumstances to be examined and indicate the path to be taken in the pursuit of high-quality transmission.

In this paper, therefore, an attempt has been made first to define terms suitable to the scientific study of faithful reproduction, second to analyse into separate constituents the types of distortion occurring, and third to lay down the general principles above referred to and give them as far as possible a mathematical form. This has been done not only for the purpose of ensuring precision and definiteness of statement, but also to enable quantitative application to be made and to prepare a foundation on which to build as knowledge of the subject progresses.

Special consideration has been given to transient phenomena because in much of the apparatus used for radio-telephony the ordinary forms of steady-state distortion can be reduced to a negligible amount. The consideration given to transients is, however, of a preliminary nature only; it is not possible to develop the study of transients in this paper beyond the simple cases of "ironless" circuits. An interesting and difficult field left open for investigation by mathematical and experimental means is the exploration of transient phenomena in circuits having impedance operators that are not single-valued functions.

In Part II, the principal types of apparatus employed in radio-telephony have been considered in as general a way as possible.

A bibliography has been attached, where detailed investigations will be found of many matters touched upon but lightly in this paper, because the presentation of matter covering so wide a field seemed to exclude extended investigations that had already received very full treatment as self-contained publications.

Introduction.

It may probably be claimed justly that the art of reproducing the human voice or instrumental music has reached higher perfection in the direction of electrical loud-speaking apparatus than in the gramophone. It is not unlikely that the cause of this is directly traceable to the fact that the electrical transmission of speech has important commercial application in the telephone and that very extensive research has been possible and necessary with the funds available to the large public-utility companies which have to do with the telephone.

Whether or no these hypotheses be accepted, there is no question at all that almost the only available information on the nature of speech and the effect of distortion is the result of research carried out for the purpose of telephony. It is probably not generally appreciated how far research has gone in the matter of improving and standardizing the quality of speech transmitted by telephone lines and cables.

In the early days of telephony the economic factors were such that the principal problem was that of securing sufficient speech volume at the receiving end; almost from the first it was realized that the instruments and lines distorted the speech and lowered the intelligibility, but it was possible to erect lines in which the speech volume fell below a commercial value long before the line attained such length as would cause serious distortion. The advent of loading coils increased very considerably the distance over which telephonic communication was possible, but loading also brought with it on cables an improvement in the quality of the received speech. Finally, the invention of the thermionic valve, to which radio-telephony owes its development, made possible the only really successful telephone repeater by means of which it is possible to transmit speech unlimited distances over land.

The telephone repeater brought with it a host of new problems, to most of which intensive research gained a speedy solution; above all, however, it reversed the order of relative importance of speech loudness and speech intelligibility; it became economically possible to obtain sufficient speech volume at the end of the longest line, but no improvement in intelligibility attended the increased range. Further, the results hitherto considered to be commercial left much to be desired; even at the present time telephonic communication is carried on with only about 50 per cent of the syllables correctly heard, the remainder being guessed by the context. When, however, unfamiliar names, isolated letters or figures are to be transmitted, the context is of no assistance and it is a matter of common experience that very great difficulties are encountered.

Definitions.

The subject of faithfulness of reproduction in radio transmission requires a basis of definitions and it is a matter of some care to select suitable definitions and to avoid confusing terms. The science of radio-telephony has developed rapidly, and has specialized for various obvious reasons along its own lines without much regard to the sister science of line telephony. This has led to some confusion; such terms as transmitter, receiver, high frequency, etc., mean one thing to a telephone engineer and another to a radio engineer. As this paper will deal with ground common to both sciences, and it is hardly possible to alter the accepted

significance of telephone terms, the following definitions will be adopted :—

The terms "high frequency" and "low frequency" will not be used, but instead the terms "radio or carrier frequency" and "speech frequency or audio frequency."

"Transmitter" and "receiver" will be used to designate the corresponding telephone instruments known in the radio art as microphones and headphones.

The complete sending or receiving apparatus will be called a transmitting set or receiving set respectively.

Turning now to the definitions with which reproduction is to be studied :—

The *Articulation* of a reproducing system is the average percentage of monosyllables correctly received when conveyed by the system without context of any kind. Articulation measured in this way is a function of the ability of the observer as well as of the reproducing system.

The *Intelligibility* of a reproducing system is the percentage of ideas correctly received when conveyed by the system and expressed in the form of short sentences. Intelligibility is a function of articulation.

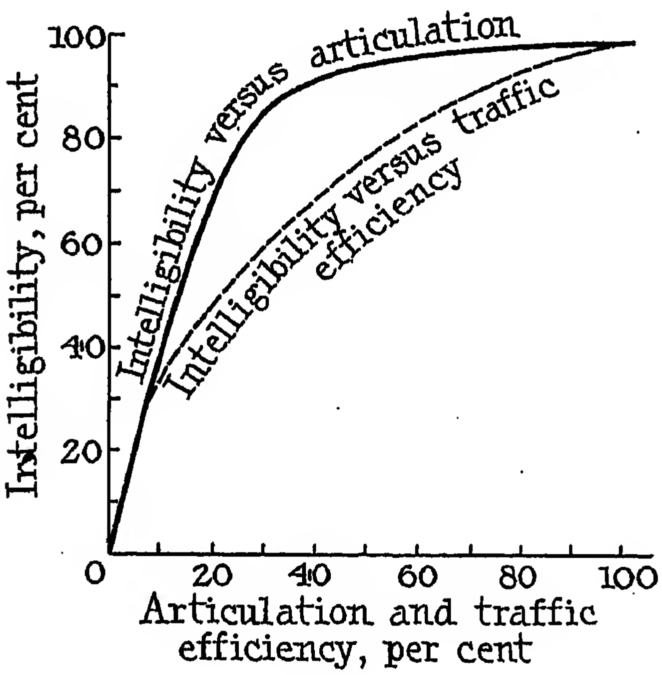

Fig. 1.

The *Traffic Efficiency* of a reproducing system is inversely proportional to the time taken to convey a single simple idea over the system.

Fig. 1 shows the relationship that has been experimentally established between articulation, intelligibility and traffic efficiency.

The foregoing definitions have to do with the capability of a system for transmitting ideas by means of speech. The coming of broadcasting calls for far more than the reproduction even of perfectly intelligible speech. Natural reproduction of the human voice and of music is required, and it is quite possible to obtain a high degree of speech quality as defined above without the reproduced voice sounding at all natural.

It is not at present possible to specify degrees of naturalness or degrees of perfection in reproducing music, though it is obviously possible to lay down the theoretical conditions for the exact reproduction of speech or music. For the present the following semi-defined quantities must be recognized :—

Naturalness is the similarity of reproduced speech or music to the original, apart from such properties as can be specifically defined under speech intelligibility.

Perfection of Reproduction is the total degree of similarity of reproduced speech or music to the original, taking into consideration naturalness and those factors which affect intelligibility.

In these two definitions it has been assumed that the intelligibility of a reproducing system which, as defined, refers to speech only is of some significance when the system reproduces music. This assumption is a very doubtful one, and it is probable that "Perfection of Reproduction" is the only heading under which the reproduction of music can be properly considered. For example, it has probably been observed by all who have had occasion to use a number of different loud-speakers that some types are better than others for speech, while some of those that are worse for speech are better for music; sometimes, even a receiver is found which reproduces a particular type of musical instrument very well indeed but is poor for other music or speech. In many ways, however, the perfection of reproduction for speech is a good all-round test of the characteristics of the system, and when speech is well reproduced music also will generally be well reproduced.

Part I.

Defects of Reproduced Speech.

Reproduced speech may suffer from several distinct kinds of distortion, all of which are generally present to some extent.

It is necessary to consider speech or music as capable of being expressed as a Fourier series. Strictly speaking, only vowel-like sounds or musical tones, i.e. sounds which can be indefinitely sustained, can be expressed as a Fourier series, but by a well-known extension a wave-form which is not repeated can be expressed in a similar form, and it is commonly accepted that problems in telephonic transmission may be regarded as steady-state problems; that is to say, all transients are neglected. This mode of regarding transmission tacitly neglects one form of distortion and will have to be revised. The consonant sounds are in general transients, and all the reproducing apparatus should be capable of reproducing these transients faithfully; more will be said on this at a later stage.

In so far as steady-state conditions may be assumed, the distortion that may occur is due either to the ratio of reproduction being different for different single frequencies (frequency distortion), or to the reproduction of different amplitudes at any given frequency in different ratios (amplitude distortion). In the latter case the distortion produced is two-fold; first, the intensities of the sounds are not heard in their proper ratio, crescendo passages, for example, perhaps failing to show any appreciable crescendo effect; and second, a number of frequency components are introduced which were not in the original sound.

It is apparent that another variable, namely "phase,"

may be distorted, but it has been well established * that the relative phase of the reproduced frequencies makes no appreciable difference to the sound heard, although the shape of the wave-form may be very greatly changed by alterations of phase.

There is yet another kind of distortion which is of a somewhat different character and is caused by the non-linear relation between the response of the ear and the energy intensity of the sound heard.

It is evident that if two sounds, one of which has twice the energy intensity of the other, are produced by a system which is capable of giving out these two sounds always with the same ratio of intensity but at different levels of absolute intensity, then because of the non-linear characteristics of the ear as regards both frequency and amplitude † they will only be interpreted in their correct ratio if the ear hears them at the same level of intensity as the original sounds would have been heard. Receiving apparatus ought therefore to be adjusted to give about the same volume of sound as is being used in the broadcasting studio, and if it is incapable of giving the necessary output without introducing other kinds of distortion, ideal results cannot be obtained.

Frequency Distortion.

Reference has been made to the distortion arising from amplification of various frequencies to unequal degrees: this is called "frequency distortion" and is at the same time both the simplest kind of distortion and the most difficult to eliminate from some of the apparatus used.

The effect of frequency distortion on music can be easily conceived; certain notes will ring out loudly while others will be lost; again, the higher harmonics which give timbre to the notes will perhaps be lost, making it hard to identify the instrument that is being played. As regards speech, the very low audio frequencies up to, say, 500, and to a less extent the high audio frequencies, are responsible for naturalness and those characteristics which enable one to distinguish one voice from another. The range from 500 to 1 500 carries most of the loudness and a considerable amount of the intelligibility. The range from 1 500 upwards is concerned less in the loudness of the sounds heard but is of supreme importance in securing high intelligibility, that is in enabling every sound to be correctly heard and interpreted without mental effort.

It has been established ‡ that higher audio frequencies can be masked, according to their intensity, by tones of lower pitch, so that if some of the higher audio frequencies required in speech are reproduced in less than a certain ratio to the lower audio frequencies they might as well be absent altogether for all the effect they are capable of producing in ameliorating the quality.

The circumstances that give rise to frequency distortion have in general an effect upon the transmission of transients. For example, suppose there is an electrical or mechanical resonance in the apparatus with a single free period. The equation of a series resonant system may be written

$$m\frac{d^2y}{dt^2} + r\frac{dy}{dt} + ky = \frac{d}{dt}F(t) = F'(t) \quad . \quad . \quad (1)$$

where $F(t)$ is the applied force expressed as a function of the time; m, r and k are the inductance, resistance and capacity or equivalent mechanical quantities of the system; then y represents current or velocity.

In (1) substitute $\frac{r}{m} = 2\beta$; $\frac{k}{m} = \omega_0^2$; $\frac{d}{dt} = D$; the equation becomes

$$\frac{1}{D}(D^2 + 2\beta D + k)y = \frac{1}{m}F(t) \quad . \quad . \quad . \quad (2)$$

Then the steady-state solution when $F(t)$ is a periodic force with angular velocity ω is

$$y = \frac{F'(t)}{m\{(\omega_0^2 - \omega^2)^2 + 4\beta^2\omega^2\}^{1/2}} \quad . \quad . \quad (3)$$

a formula sufficiently well-known to require no comment, since it represents the current taken by a series resonant circuit in terms of the inductance, natural frequency, applied frequency and damping. It may perhaps be worth while pointing out that if in (3) m alone varies, ω_0 and r being held constant, the tuning becomes sharper as m increases, for the maximum amplitude of y is unchanged while all other values of y are reduced when m increases. Thus lightness of the moving parts of mechanism in the reproducing system is essential.

Now examine the capabilities of the series resonant system represented by (1) for responding to transient forces.

Suppose that a unit steady continuous force is suddenly applied so that the right-hand side of (2) becomes $(1/m)(1)$ where (1) signifies that the force is zero before time $t = 0$ and unity when t is positive.

The well-known solution of the equation is now

$$y = \frac{e^{-\beta t}}{m\gamma}\sinh \gamma t \quad . \quad . \quad . \quad . \quad . \quad (4)$$

in which $\gamma^2 = \beta^2 - \omega_0^2$. Expression (4) applies when the system is heavily damped and γ is real. With less damping γ is imaginary, and the solution is written as in (5) if γ is still treated as real, while if γ is zero the system is critically damped and the solution is as given in (6), thus:—

$$y = \frac{e^{-\beta t}}{m\gamma}\sin \gamma t \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$y = \frac{te^{-\beta t}}{m} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

From these three solutions it is seen that if free oscillations depending only on the structure of the system are to be avoided, the damping must be at least critical.

The further application of these formulæ depends upon the circumstances of each case; the system may be a circuit coupled to the grid of a valve, and the formula must be developed according to the coupling adopted. Thus if it is the voltage due to the current y through a resistance r in a series resonant circuit that operates on the grid, (4), (5) or (6) applies, after multiplying by r; but if it is the voltage across the

* See Bibliography (1). † *Ibid.*, (5). ‡ *Ibid.*, (2 and 9).

inductive element of the circuit that is effective, the formulæ have to be operated on by $m(d/dt)$; and if it is the voltage across the condenser that is effective, (4), (5) or (6) must be integrated with respect to time and multiplied by $m\omega_0^2$. In the last case only will the steady applied force ultimately produce a steady corresponding effect.

The response to a transient force of the type considered has been calculated for three cases, and is shown by the curves of Figs. 2 and 3. Fig. 2 shows the value of y (current or velocity) and Fig. 3 the integral of y proportional to displacement or electric charge.

By differentiation of (4), (5) and (6) it is found that the initial slope (at $t = 0$) of the response curves in Fig. 2 is equal to $1/m$, indicating again the importance of small moving mass in any mechanical system. Figs. 2 and 3 show that increased damping retards the response after the first moment.

To obtain a good approximation of the value of the displacement to the value of the applied force, it is essential that m should be small and the initial slope of the y curve correspondingly steep. The damping should be at least critical in order to prevent oscillations,

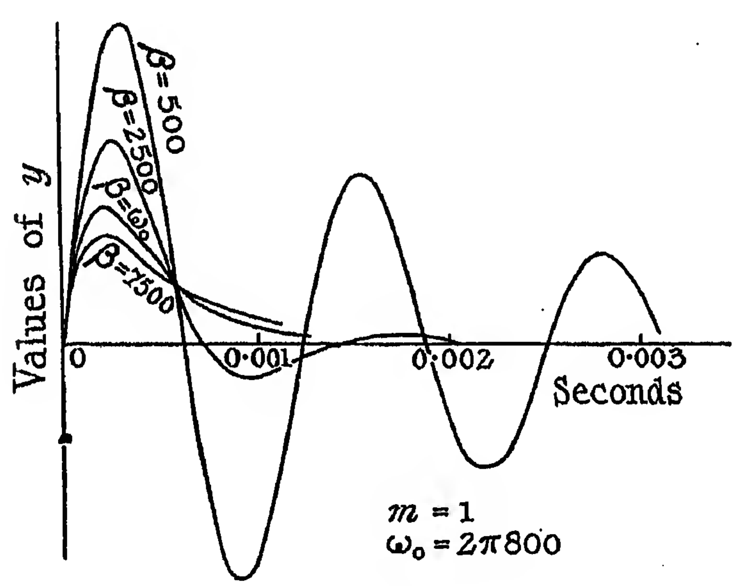

FIG. 2.

and the natural frequency should be high so as to limit the time over which the disturbance lasts.

Examination of Equation (3) shows that high natural frequency and small mass are also the requisites for good reproduction under steady-state conditions, while high damping must also be added if the natural frequency is not well outside the frequency region to be reproduced.

The case of a series resonant system has been given fairly fully because of its inherently great importance; e.g. in the simple radio receiving circuit (Fig. 4) the aerial is a series resonant circuit, and the important quantity is the voltage across the inductance. Similarly (2) is a series resonant circuit provided that the grid conductivity can be neglected. Again, if the grid side of an intervalve transformer has high capacity and the grid filament circuit has negligible conductance, a series resonant circuit similar to (2) is formed. Lastly, the mechanism of a telephone receiver or loud-speaker is a resonant system of the same type expressible by Equation (1).

Parallel resonance circuits are met with in tuned anode circuits, in the plate circuit side of intervalve transformers having high capacity, and so on.

There is no reason to suppose that a reproducing system will be called upon to respond faithfully to a transient of the kind discussed in Equations (4), (5) and (6), but the results have been given in some detail because the response of the system to any non-periodic

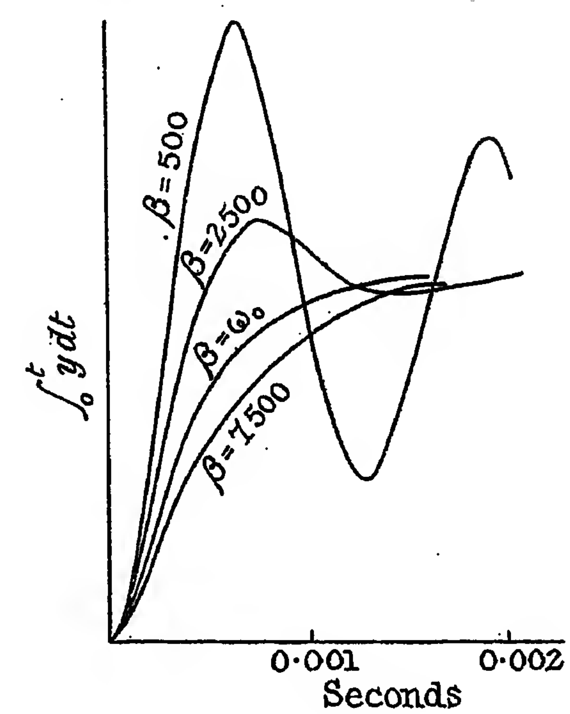

FIG. 3.

applied force, or to any change of amplitude or frequency of a periodic force, can be obtained from its response to a suddenly applied steady force. It therefore seems reasonable to regard the response of a system to a suddenly applied steady force as a good indication of its behaviour towards the transients that will actually occur in speech and music.

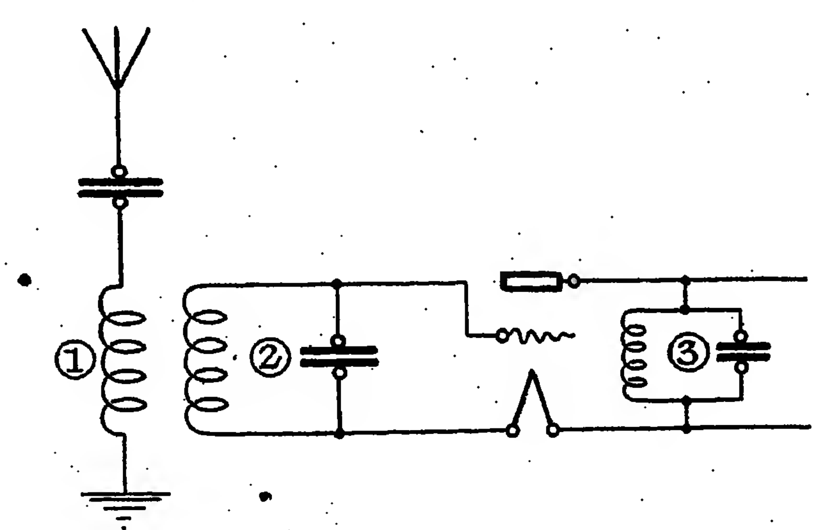

FIG. 4.

It is not proposed to examine in detail the many different types of elementary circuits and mechanisms involved in telephonic transmission; the methods of doing so have been developed elsewhere, and the possible combinations are very numerous. For example, the total damping of the system can always be divided into two components, one useful, the other wastefully dissipative; in the case of an electrical circuit element

there may be series or parallel resonance, and the total effective resistance, or either of its two components, may be in series or in parallel with either the inductive or capacitive element. It may, however, be noted that since parallel circuits contain elements similar to the elements of series resonance circuits, the potential, kinetic and dissipative energies of a parallel system enter into Lagrangian dynamical equations of the same form as series systems but with different co-ordinates; the conditions for most faithful response can be derived by superposition of variables effective in series circuits, and will therefore be the same in parallel combinations as in series combinations. When we are concerned with the shunting effect of a parallel resonance circuit, so that attention is not directed to the response in the resonance circuit (e.g. in a tuned anode circuit), the same conditions apply, for it is only by the quick and faithful response of the bridging resonance circuit that the back E.M.F. necessary to maintain the form of the impressed voltage can be secured.

Different Distorting Elements, Additive or Otherwise.

The next inquiry while general principles are under study is the consideration of the effect, cumulative or otherwise, of two unilaterally coupled series resonant elements in the transmission chain. There may be two parts of the transmission system which are resonant in character but so situated that they do not react on each other, and their natural frequencies are independent. So far as frequency distortion goes, it is evident that if the two resonances have approximately the same damped frequency the distortion will be intensified, whereas if they have suitably different frequencies the overall response characteristic may be levelled up and, to a certain extent, improved.

Again, it is evident that the steady-state frequency-distortion characteristic can be levelled up by the application of networks having suitable characteristics; as a simple example, the peaked form of the current/frequency curve in a series resonant system can be reduced to a less peaked form by the addition of a suitable parallel resonance circuit, which may be separated from the series circuit by a vacuum tube to prevent interaction of the impedance of the two elements.

It is shown in the next section that the effect of successive distortions on the transient phenomena may be judged by its effect upon the steady-state frequency distortion.

The Response-frequency Characteristic as a Criterion of Quality.

The frequency distortion of any element of a reproducing system is shown by plotting the output or response against the frequency for an input voltage or force of constant amplitude. An element of the system is here taken to mean one complete closed circuit, or its mechanical equivalent.

It is seen from Equations (3) and (4) that in the specific instance examined the reproduction of a transient depends upon β and ω_0, as also does the steady state, and the amplitude of reproduction is in both cases inversely proportional to m.

It is shown in an Appendix that this relation is general and that the response-frequency characteristic is related to the response for transients as well as for the steady state as far as analytical methods are applicable.

In order to obtain a more general conception of the performance of a system in respect of transients, suppose that the force acting is $E(t)$, and the response is given by $Y(t)$, both being functions of the time. Then these two functions are related (in an invariable system) by a third function, which depends upon the constants of the system only and may be thought of for the moment as a mutual admittance, as it actually is in the electrical case; it can therefore be expressed in a generalized way as a function of the circuit constants, and the operator d/dt which will be denoted by q. Thus $E(t)$ and $Y(t)$ are related by an expression of the form

$$Y(t) = f(q)\, E(t)$$

Now in solving such an equation for the steady state when $E(t)$ is a sinusoidal force, the usual procedure is to substitute (jn) for q. Following the methods of Heaviside we may regard $f(jn)$ as the generalized mutual admittance effective with its proper value of n for every real frequency in the Fourier integral expressing a transient applied: thus, as is shown by T. C. Fry,* we write the applied force

$$E(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} dn \times e^{jnt} \int_{-\infty}^{+\infty} d\lambda E(\lambda) e^{-jn\lambda} \quad . \quad . \quad (7)$$

and
$$Y(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} dn \times f(jn) e^{jnt} \int_{-\infty}^{+\infty} d\lambda E(\lambda) e^{-jn\lambda} \quad . \quad (8)$$

Here the response to the transient applied force is seen to depend on the mutual admittance expressed in complex form, that is, as a modulus with an angle. The relation of response to input, which ordinarily forms the frequency-distortion characteristic, is determined as the modulus only of the mutual admittance without regard to angle. In the steady state this is justified, since it is experimentally well established that the alterations of wave-form resulting from alterations of phase do not appreciably affect the sound heard. Under transient conditions, however, the infinite series of frequencies summed in the Fourier integral occur as single waves only, and the shape of the response may be very considerably altered by phase distortion. It cannot be claimed that there is definite experimental evidence that the change in the shape of a transient resulting from changes in phase of its component frequencies can be appreciated by the ear, but it is difficult to see how one transient is to be distinguished from another if this kind of distortion does not matter. It is not difficult to suppose that an harmonic analysis of sustained sounds is made by the ear, and that the phase elements are discarded. It is more difficult to see how the ear could carry out such an artificial process as the reconstruction and identification of a Fourier integral from a received pulse that differed materially in character from the original force. The problem of reconstructing the original transient force from its

* See Bibliography (45).

distorted reproduction is obviously incapable even of being uniquely mathematically solved in the absence of data regarding the law of distortion.

As a commentary on the foregoing remarks we may note that the most difficult sounds to reproduce with sufficient accuracy to make them easily identified are p, b, t, d, k and g, the stop consonants which are truly transient in character. Other difficult consonants are f, v, th and s, but these owe their difficulty to the relatively high audio-frequency region involved in their formation.

If the English consonant sounds are examined, it will be found that many of them, like the last group mentioned, are capable of being sustained and are therefore vowel-like in character. W in "away" is clearly a transitional sound, practically composed of a series of vowels in such quick succession that the steady state can scarcely be established. It is probable that the vowel-like consonants are to be regarded in the same way as W, since they frequently seem to be merely a way of beginning a true vowel and are therefore transient in character.

Amplitude Distortion.

The response-frequency characteristic of any element of a system has already been defined from the point of view of frequency distortion. If the ratio of output to input is a function of the amplitude, the definition must be extended to a more generalized form.

If there is no amplitude distortion the ratio of output to input, voltage or force, for any element defines the frequency distortion, thus

$$V_2 = G(n)\,V_1 \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where G is the frequency distortion, a function of frequency only.

If amplitude distortion is present, V_2 will vary non-linearly with V_1 at a given frequency, and the relation may be written

$$V_2 = G(n)H(V_1) \quad . \quad . \quad . \quad . \quad (10)$$

Frequently $H(V_1)$ may be expressed in the form

$$H(V_1) \propto V_1^a \quad . \quad . \quad . \quad . \quad . \quad (11)$$

This kind of distortion is found in iron-core coils, on account of the non-linearity of the BH curve of the iron, and also in valve circuits on account of the curvature of the valve characteristic. In the same two cases hysteresis may be present, in which case the distortion will be represented approximately by

$$H(V_1) = \hat{\mu} V_1^a \quad . \quad . \quad . \quad . \quad . \quad (12)$$

where $\hat{\mu}$ is a complex operator.*

In all these cases a single-frequency impressed force V_1 produces a response in which the fundamental is not proportional to the force, and in which there are a large number of different frequency components having precisely the same effect as a variable superposed noise.

It should be noted that there are four kinds of amplitude distortion, according to whether the function H is single-valued or double-valued, and whether it is symmetrical or asymmetrical about the point at which the system is in equilibrium with no impressed forces.

* See Bibliography (46 and 47).

The Measurement of Intelligibility.

In telephone work it has been found necessary to have some means not only of testing apparatus for the speech articulation it is capable of transmitting, but also of specifying the result of such tests, in terms of some characteristic that will measure all possible kinds of distortion in apparatus of different nature.

For many years it has been customary to recite lists of meaningless monosyllables over a telephone system to be examined, and to determine the proportion of syllables accurately recorded. For this purpose a large number of lists (over 150) of syllables have been compiled, each list being arranged to give equal weighting to the different elemental speech sounds.

The technique of these tests has been developed to the point where definite and significant results can be obtained. These "articulation percentages" depend, however, upon the acuteness or alertness of hearing of the observer, and also upon the amount of practice obtained. Reference has already been made to Fig. 1, in which is exhibited the correlation between intelligibility and the articulation percentages obtained with a particular set of lists.

Some idea of the importance of the various speech-frequency regions in giving faithful reproduction will be seen by examining the curves shown in Fig. 1 of Mr. Sandeman's introductory paper to a recent discussion on loud-speakers.* These curves show the effect upon articulation of transmitting, without distortion, the frequencies from zero to n only, or from n upwards only for different values of n.

Naturalness and Intelligibility.

Intelligibility has been defined as the inherent ability of a reproducing system to convey the elements of speech that are important from the telephonic point of view for conveying ideas; it is, as has been shown, a function of articulation. By "naturalness" we understand all the other properties of reproduction, additional to those which have been found to have a measurable effect on the observed articulation. For example, the insertion of a small condenser in a telephone system may have very little effect on the articulation or intelligibility of a system, but may make a great difference to the character of the sounds heard.

It seems probable that naturalness in speech is to be associated with the vibrations of the vocal chords, for Sir Richard Paget has shown † that the essential qualities of each vowel are inherent in two or more reinforced frequencies, and that vowels and unvoiced consonants of perfect intelligibility may be sounded without the assistance of the vocal chords, that is by whispering.

If, then, naturalness of speech is concerned in just these low audio frequencies which do not greatly affect

* *Journal I.E.E.*, 1924, vol. 62, p. 275.
† See Bibliography (20).

the observed articulation, it may be expected that a good idea of the behaviour of a reproducing system for general purposes is gained by observing the capability of articulately reproducing speech, together with the degree of tone resemblance between the original speech and the reproduced speech.

Modulation and Demodulation.

By modulation we understand the distortion of a carrier current in some arbitrary manner by speech-frequency currents, so that the modulated carrier contains the speech-frequency elements. The carrier may be modulated in various ways, the essential requirement being only that the modulating current shall definitely change the carrier in some reversible manner, and not be merely superposed upon it. The distorted or modulated carrier can then be demodulated by the receiving apparatus; demodulation—a better word for telephony than detection—is the converse of modulation, and is the process of disentangling or recovering the original speech-frequency currents from the modulated carrier.

Without going into the details of the different methods used to procure modulation, let it be assumed that the modulated carrier of angular frequency c is represented by

$$B(1 + A \sin pt) \sin ct \quad . \quad . \quad . \quad (13)$$

when a single speech frequency of angular frequency p is operating and B is the amplitude of the unmodulated carrier. Then, when a number of different speech frequencies are present, the form of the modulated carrier will be

$$B(1 + \sum_{0}^{P} A_p \sin pt) \sin ct \quad . \quad . \quad . \quad (14)$$

where the upper frequency-limit P may be taken as equivalent to 6 000 periods per second for speech, and some higher value for music.

Let A be the maximum instantaneous value of modulating voltage; it is clear that this must be less than unity or overmodulation will take place, a phenomenon associated, as will presently be shown, with distortion in the demodulator. Thus, for all possible frequencies and for all possible intensities to be transmitted, A must be less than unity.

The process of demodulation depends upon the proper use of an asymmetrically distorting circuit, the particular form of distortion being approximately represented by saying that the amplitude of the demodulated signal varies in most cases as the square of the modulated carrier amplitude.

The demodulated voltage will therefore be proportional to

$$B^2 \sin^2 ct(1 + \Sigma A_p^2 \sin^2 pt + 2\Sigma A_p A_q \sin pt \sin qt + 2\Sigma A_p \sin pt) \quad . \quad . \quad (15)$$

With these assumptions, and since the maximum value of A must be less than unity, the average value of A will be considerably less than unity, in practice certainly not more than about 0·6 for speech (the usual percentage modulation), and lower still for music. The terms of second degree in A then tend to disappear as the percentage modulation is lowered, and the signal becomes proportional to $2B^2 \sin^2 ct \Sigma A_p \sin pt$, that is, it is proportional to the original signal and to the square of the carrier.

We see then that with these (the ordinary) assumptions there is distortion in the process of modulation and demodulation, viz. the two terms of second degree, and that the importance of these terms increases as the percentage modulation is raised; in fact, the maximum value of A should not be allowed to approach unity, since all such amplitudes will appear in the demodulated current accompanied by large parasitic or unwanted components.

Our next inquiry will be into the nature of the distortion due to the parasitic frequencies represented by the quadratic terms.

Consider first a term in the demodulated current of the form

$$2(A_p A_q \sin pt \sin qt) \sin^2 ct \quad . \quad . \quad . \quad (16)$$

The two frequencies p and q modulate each other, or in the language of speech-frequency currents they produce beats, or sum-and-difference tones; the preceding expression may be written

$$A_p A_q \sin^2 ct \{\cos (p - q)t - \cos (p + q)t\} \quad . \quad (17)$$

so that the unwanted terms in the received signal consist of tones of frequency $(p + q)$ and $(p - q)$, one or both of which may be in the frequency zone transmitted and may cause beats or interference with tones of the same or near frequency which are legitimately received as part of the desired signal. Similarly, the symmetrical terms of second degree are equivalent to a single double-frequency parasitic tone.

The question will now naturally be raised as to whether, and under what conditions, it is possible to secure distortionless modulation and demodulation. It is readily seen that if linear modulation as in (14) is used, and demodulation is also linear, the required result will be secured. Linear demodulation, however, requires the demodulator to have a linear characteristic, and at the same time be a rectifier; that is, in the case of a valve using plate-current demodulation the plate-current/grid-voltage characteristic would have to be linear up to some point, and also beyond that point, but with a different slope. It is well known that the effect of space charge and varying voltage along the filament prevent the realization of this ideal demodulation.

It has also been suggested * that distortionless reception can be secured when demodulation follows a square law if

$$I^2 - I_0^2 = KE$$

where I is the amplitude of the modulated carrier,
I_0 is the amplitude of the unmodulated carrier,
K is a constant, and
E is the signal to be sent.

If $\Sigma A_p \sin pt$ is the signal the law of modulation is then

$$I = (K\Sigma A_p \sin pt + I_0^2)^{1/2} \quad . \quad . \quad . \quad (18)$$

If the received signal is proportional to I^2 it is received without distortion.

* See Bibliography (44).

Such a law of modulation gives, however, very much larger changes in the amplitude of the modulated carrier for relatively small modulating voltage than for voltages sufficient to give complete modulation. The result is that when demodulation fails to approximate to the square law, and especially if it approaches a linear law, there is serious distortion. It has been shown by Moullin and Turner that for strong signals the demodulation is likely to follow a linear law.

Another point in connection with modulation of this kind is that the law is difficult to realize in practice. In general, modulation will not exactly follow a linear law, and demodulation will not exactly follow a square law; in either case amplitude distortion will be introduced, and it is therefore generally accepted that moderate linear modulation is best.

In the sending aerial circuit, and in the receiving circuits, the modulated carrier undergoes distortion in proportion to the sharpness of tuning. If the expression for modulated carrier is expanded in the form

$$\sin ct + \tfrac{1}{2}\Sigma A_p \{\cos (c - p)t - \cos (c + p)t\} \quad . \quad (14a)$$

it is seen to consist of terms which are sum-and-difference frequencies of carrier and audio frequencies, forming, as is well-known, the two side bands. As the response of the resonant tuned circuits is a function of frequency, the higher audio frequencies in the received signal will be reproduced in smaller proportion than the lower audio frequencies. In the absence of reaction and at the shorter wave-lengths this distortion is, however, not serious, even when there are three or four such tuned circuits involved in the transmission.

A complete study of modulation and demodulation would take up too much space, especially if the different methods employed were discussed. The principles involved have therefore been given in their most general form, and further information to which the principles here given may be applied can be obtained from many excellent investigations that have been published—a few of these are given in the bibliography at the end of this paper.

Part II.

The foregoing discussion has described the broader principles concerned in the avoidance of distortion. Where possible these principles have been expressed in precise mathematical forms for the purposes of concise definition and in order that they may be used as the basis of calculation and analytical study, as knowledge of the subject progresses. We shall now turn our attention in greater detail to some of the elements commonly used in radio-telephony.

It is natural that the first element studied should be the transmitter, and here at the beginning of the radio-telephone system is a problem of no mean proportions. The transmitter must fulfil the following conditions:—

Its electrical voltage output at all frequencies from 20 per second up to some undetermined high audio frequency—say about 10 000 per second—must be a faithful reproduction of the pressure in the air due to the sound to be transmitted.

This condition, of course, implies absence of frequency distortion and amplitude distortion both symmetrical and asymmetrical.

The carbon transmitter used in ordinary telephony depends for its efficiency upon the judicious use of a certain amount of resonance, permitting unavoidably a definite and known amount of frequency distortion; it is, moreover, guilty of amplitude distortion, as any instrument must be which operates by the variation of resistance unless the resistance variation is very small. Asymmetrical distortion is also present, due to the non-linear variation of carbon resistance with pressure (unless it is specially compensated as in what is known as a "push-pull" arrangement). It is evident, in view of the enormous amount of study that has brought the carbon telephone transmitter to its present state of commercial efficiency and quality, that no high-quality transmitter can at present be made with anything like the same transmitting efficiency. This is, however, not serious. Thanks to the high degree of distortionless amplification obtainable by valves, the lower limit of permissible efficiency is only controlled by the degree of electrical disturbance picked up by the transmitter leads, and the amount of noise inherent in the early stages of the amplifying system.

Excellent transmitters can be made by securing very high natural frequencies with high damping in the mechanical system, and there is then not much difficulty in avoiding amplitude distortion. Alternatively, arc and flame transmitters have been made in which there is no mechanical system; both mass and stiffness are negligible, but amplitude distortion has to be considered. The author has no information on this aspect of the case, but it does not seem likely to introduce any serious difficulties.

It is hardly necessary to add that electrical and acoustical resonances, as much as mechanical resonances, must be avoided in connection with the transmitter as elsewhere.

So far as is known, only five types of high-quality transmitter are in use at present. In the condenser transmitter a light and tightly stretched diaphragm, heavily damped, forms a small condenser which varies in capacity with the pressure of the air. If a steady voltage E is applied through a resistance across which connection is made to the amplifier, the alternating voltage across the resistance will be proportional to the current flowing when the condenser capacity varies.* For the minute alterations of capacity resulting from the varying pressure of sound incident on the diaphragm the amplitude distortion is quite negligible, and the combination of damping and high natural frequency (about 16 000 p.p.s.) gives an almost flat frequency characteristic.

In the "push-pull" carbon transmitter a similar highly-damped stretched diaphragm operates on two carbon buttons, one on each side and so connected as to compensate mutually for the non-linear carbon distortion.* The variations of resistance are so small that the amplitude distortion arising from the reciprocal relation between carbon pressure and current is quite negligible.

In the electromagnetic transmitter a light coil with

* See Bibliography (35 and 48).

very little stiffness is made to vibrate in a magnetic field by the sound waves; the damping is partly mechanical and partly electrical. The output voltage varies directly as the frequency. The natural frequency is probably low, so that the variation of output with frequency partly compensates for the falling amplitude/frequency characteristic of the vibration, and the frequency distortion can be corrected by suitable inductance.

A fourth type of transmitter operates by the direct action of sound waves on a silent glow discharge provided with a third intermediate electrode. It has been found possible * to control the frequency distortion of this transmitter and to procure a practically flat characteristic by suitable adjustment.

In a fifth type † developed in Germany, sound waves influence the current flowing across an ionized air space between a Nernst glower and a cold electrode.

Amplifiers.

The transmitter will, in general, be connected to an amplifier or series of amplifiers, and it is proposed to

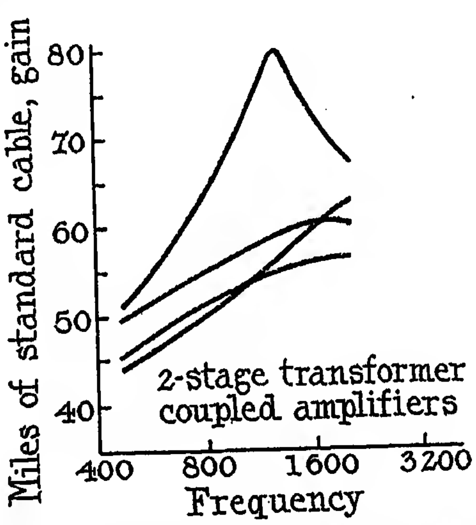

Fig. 5.—Frequency-distortion curves of speech-frequency amplifiers for radio receiving sets tested by the American Bureau of Standards.

consider next the problems of amplification, but it should be understood that the remarks about to be made apply equally to audio-frequency amplifiers used in the receiving apparatus.

It has been pointed out to the author that at a recent discussion on loud-speakers at this Institution, two telephone engineers (of whom the author was one) both assumed without comment that undistorted speech currents at any required level of volume could be delivered to a receiver, while other speakers spoke of the difficulty or impossibility of securing undistorted amplification. It is also noticeable that the technical Press has published several articles recently on high-quality resistance-coupled amplifiers. This criticism of speech amplifiers, in general, appears to have some foundation, as is shown by Fig. 5,‡ which is a reproduction of the frequency-distortion curves of four representative makes of speech-frequency amplifiers for radio work. These curves were published by the American Bureau of Standards. Fig. 6 is the frequency-distortion curve of another well-known make of loud-speaker amplifier.

To a telephone engineer these response characteristics are an amazing revelation; for several years telephone repeaters have been regularly manufactured to requirements holding the variation of gain over the

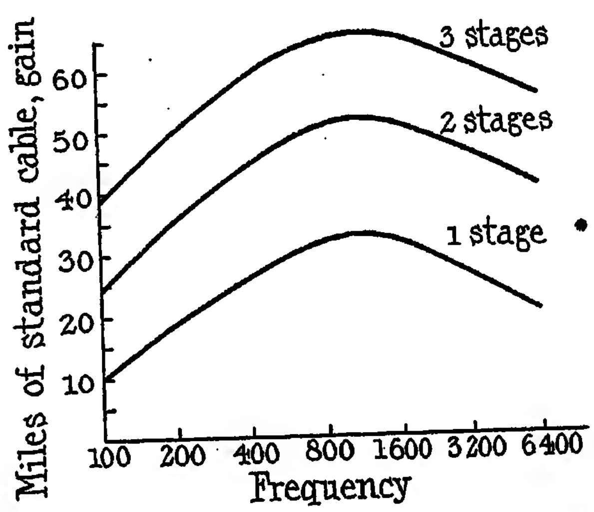

Fig. 6.—Frequency-distortion curves of a loud-speaker amplifier.

range 200 to 2 600 p.p.s. within a range of $1\frac{1}{2}$ miles of 800-cycle-mile standard cable. Figs. 7 and 8 show characteristics of good amplifiers for radio-telephony employing either inductance and condenser or transformer coupling, and should settle definitely the question of whether or not amplification without distortion is possible, at least as far as frequency distortion is concerned. It will presently appear that amplitude distortion can readily be reduced to an almost negligible amount.

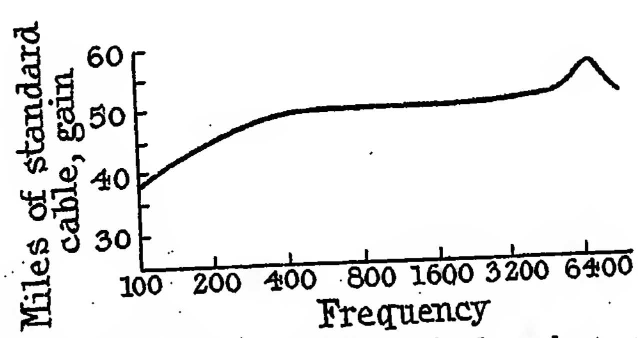

Fig. 7.—Characteristic of a two-stage loud-speaker amplifier of good quality with transformer coupling.

We shall investigate the conditions for avoiding distortion under three headings :—

(a) The valves.
(b) The coupling.
(c) The combination of valve and coupling.

(a) In order that an amplifying valve may operate without distortion, the grid-voltage/plate-current characteristic under the working conditions must be linear over a certain range, and the instantaneous voltage applied to the grid circuit must always lie

* See Bibliography (34).
† *Ibid.*, (43c).
‡ The ordinates are plotted as the number of miles of standard cable having an attenuation loss at 800 p.p.s. equal to the gain of the amplifier at each frequency. Standard cable at 800 p.p.s. has an attenuation constant of 0·109 per mile. The amplification has been plotted in miles of standard cable, that is logarithmically, because it is known that the apparent loudness of two sounds is more nearly proportional to the logarithm of their energy intensities than to the intensities themselves. In this respect the sensation of hearing appears to follow a law similar to the Weber-Fechner law for optical sensation.

between the values of abscissæ which correspond to the limits of linearity. These conditions will be approximately fulfilled when the valve has suitable capacity for the work it has to do if the grid voltage and plate voltage are correctly chosen. A rough guide in choosing these relations is that the maximum alternating voltage applied to the grid should not exceed the amount of the grid bias (including any grid bias that may be due to a high-resistance leak in series with the biasing potential); the actual values should, however, be chosen after a study of the dynamic characteristic has been made, or at least after the dynamic characteristic has been calculated from the static characteristics and the circuit constants. The effect of using a valve over too large a range of its characteristic has been discussed theoretically and experimentally by J. G. Frayne,* where also it is shown how negligibly small the distortion of wave-form becomes as the alternating voltage applied to the grid is reduced to a value commensurate with the steady grid-bias voltage.

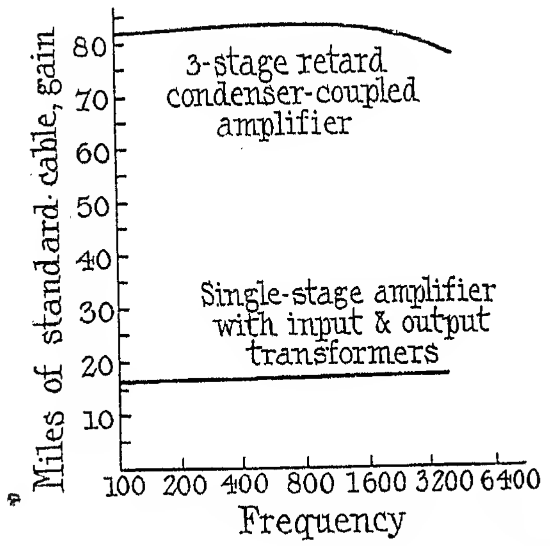

FIG. 8.—Characteristics of good-quality amplifiers for speech-input equipments.

(*b*) The forms of coupling in common use are impedance and condenser (the impedance being either a high resistance or a large inductance) and transformer coupling.

Resistance coupling naturally gives very good quality, and freedom from frequency distortion is easily secured, but it requires a plate battery of higher voltage, and a large part of the effective alternating E.M.F. in the plate circuit is lost unless an extremely high-voltage plate battery is used.

Inductance and capacity coupling has been very successfully used. The points requiring attention are that the inductance must be large enough to offer an impedance high in comparison with the tube impedance at the lowest frequencies to be transmitted, and at the same time the winding must be so arranged that the self-capacity of the coil does not approach the resonance condition at a frequency within the range to be amplified. The core must be sufficiently generously designed to prevent saturation by the plate current flowing in the windings.

Transformer coupling has the greatest overall efficiency and presents the greatest difficulty in avoiding distortion. The advantage of transformer coupling is that the voltage can be stepped up between valves, thus reducing the number of valves required for a given amount of amplification. The difficulty lies in the fact that the primary of the transformer must meet the conditions specified for inductance coupling, while the secondary, in order to get a voltage transformation of four or five, must have an impedance 16 to 25 times as high as the primary. Under these conditions the capacity of the secondary winding is only to be prevented from having serious resonance effects by extremely careful design. The hysteresis effect must also be kept low to avoid asymmetrical distortion. In spite of these difficulties, however, transformer coupling has been successfully employed in high-quality amplifiers, as has already been shown.

Another distortion, somewhat more common than it should be in audio-frequency amplifiers, is due to the curvature of the *BH* characteristic of iron, which causes a certain amount of amplitude distortion. So long as a transformer is sufficiently generously designed, it is possible to keep the variation of flux density so low that the amplitude distortion is negligible on account of the small part of the *BH* curve concerned; but many transformers are made for audio-frequency or loud-speaker amplifiers with very much smaller cores than have ever been used in ordinary telephony, although in the case of loud-speaker amplifiers the speech power applied to the transformer is much greater than that concerned in telephony.

The use of small iron cores reacts also on the frequency distortion of the circuit, because high-impedance windings must be obtained to secure high efficiency at low frequencies. Now the requisite high impedance can be secured by increasing the number of turns or by enlarging the core, but a limit to the increase in the number of turns is in practice soon reached on account of the self-capacity of the coil; thus from the point of view of frequency distortion as well as amplitude distortion a generously designed iron circuit is necessary.

(*c*) It is necessary to study the combination of vacuum tube and coupling because thermionic tubes are not, and cannot be, perfectly unilateral in their behaviour. It comes about, therefore, that the input grid-filament impedance of a tube is a function of the impedance in the plate circuit. In order to investigate this relation rigorously, it would be necessary to think of a vacuum tube as a variable electrical system; that is, the plate-filament impedance should be treated as a function of the instantaneous plate current, a class of problem which has been examined by H. W. Nichols and J. R. Carson.* For most practical purposes, however, it is satisfactory to regard the plate-filament impedance as constant, and as containing a voltage equal to μ times the voltage impressed on the grid, according to the method described by H. W. Nichols.† The various kinds of distortion that may be encountered when the grid voltages are small have been described by the present author elsewhere,‡ where it is shown that the input impedance of the tube is a function of

* See Bibliography (32).

* See Bibliography (48). † *Ibid.*, (26*a*). ‡ *Ibid.*, (25).

the impedance in the plate circuit, and consequently distortion may result if the input impedance varies greatly with the frequency. It is also shown that distortion of wave-form is indicated by a change in the reading of an ammeter in the plate circuit of a valve, and that this kind of distortion is to be avoided by making the external plate-circuit impedance high.

Reference must also be made, on account of its probable effect upon transients, to the phase distortion arising from reactive impedance in the plate circuit. It has been shown by Van der Bijl * that with inductance in the plate circuit the dynamic characteristic is an approximate ellipse having an area proportional to the alternating energy contained in the inductance (see also J. G. Frayne) †; it follows that if the inductance is sufficiently large the alternating current flowing in it can be made so small that the energy $\frac{1}{2}Li^2$ is small and the phase distortion is negligible.

Fig. 9 shows oscillograms taken with a Western Electric cathode-ray oscillograph, illustrating the elliptical form of the dynamical characteristic when the plate circuit is inductive. In Fig. 9 (*a*) the load was an inductance of 0·4 henry and in Fig. 9 (*b*) an inductance

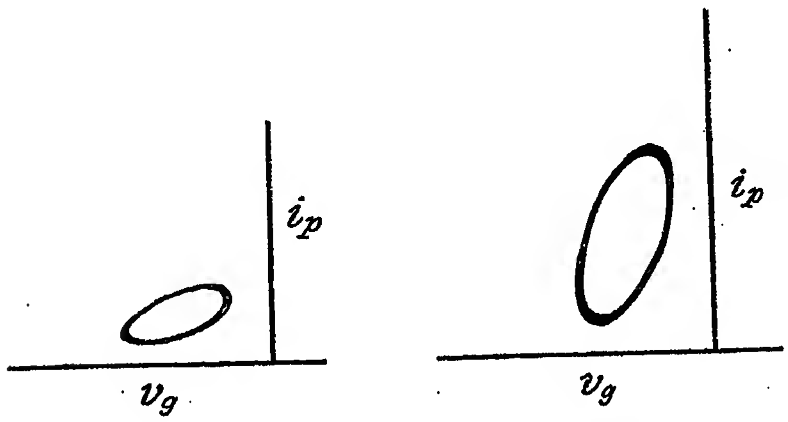

FIG. 9 (*a*). FIG. 9 (*b*).

FIG. 9.—Oscillograms taken with a cathode-ray oscillograph.

In Fig. 9 (*a*) the load was an inductance of 0·4 henry.
In Fig. 9 (*b*) the load was an inductance of 0·8 henry.

of 0·8 henry. The slope of the major axis of the ellipse is the average effective mutual admittance of the grid circuit to the plate circuit; and the ellipse itself, since the ratio of its axes depends upon frequency, indicates that the phase of the plate-circuit current will be a function of the frequency.

There is, however, an upper limit to the value of the inductance in the plate circuit, because the input impedance of the tube has an increasingly large negative resistance component for increasing plate-circuit inductances, and this tends towards oscillation; and even although actual oscillation does not occur, this condition must not be approached or excessive amplification of frequencies in the neighbourhood of the natural frequency of the system will result.

Fortunately, it is generally possible to find between the limits described a suitable value of inductance that will operate successfully over a wide range of frequencies, especially when inductance-condenser coupling is used, as the retard does not form the useful load but is only the high-tension feed; the effective plate-circuit impedance for large values of the inductance depends on the condenser coupling and grid leak of the succeeding valve which form a circuit in parallel with the inductance.

* See Bibliography (23). † *Loc. cit.*

REACTION.

Reaction is seen in its simplest form when it is applied to a radio-frequency amplifier; the output circuit is coupled back to the input circuit in any convenient manner so that the output produces an augmented input. In order to represent the arrangement in its simplest form we may ignore the inter-electrode capacities of the valve, and assume that we have a unilateral machine in which the output voltage is μ times the input voltage. We will suppose that a constant alternating voltage is applied to a series resonant circuit (the aerial), and that the voltage across the inductance is applied to the idealized voltage amplifier,

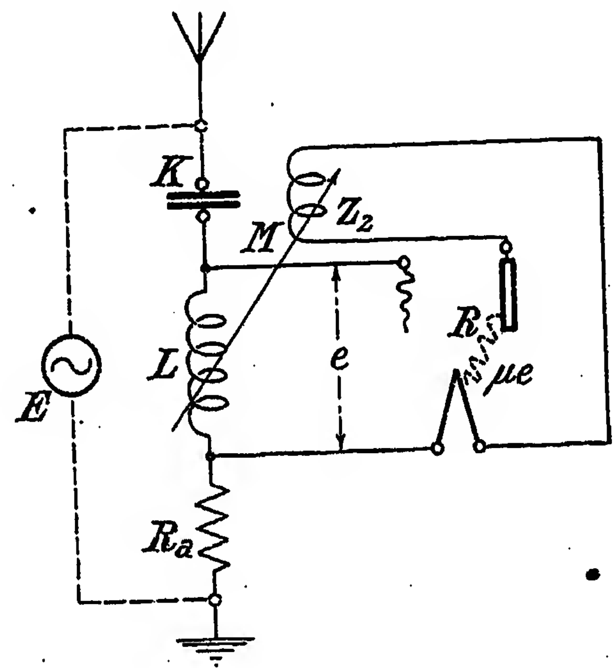

FIG. 10.

the output from which reacts on the aerial inductance (see Fig. 10).

The equations for this system at a frequency p, if Z_a is the aerial impedance without reaction, are

$$\left.\begin{aligned} x_1 Z_a + x_2 jMp &= E \\ x_1 jp(M - \mu L) + x_2(R + Z_2) &= 0 \end{aligned}\right\} \quad . \quad (19)$$

from which we derive the effective aerial impedance

$$\frac{E}{x_1} = Z_a - \frac{Mp^2(\mu L - M)}{R + Z_2} \quad . \quad . \quad . \quad (20)$$

Since M is related to Z_2 and L, it is convenient to substitute jpL_2 for Z_2 and $k\sqrt{(LL_2)}$ for M. We then get the following terms for the aerial impedance after rationalizing:—

Without reaction $\quad Z_a = R_a + jpX_a$

Real component due to reaction

$$= -\frac{p^2kLR(\sqrt{L_2})(\mu\sqrt{L} - k\sqrt{L_2})}{R^2 + p^2L_2^2} \quad (21)$$

Imaginary component due to reaction

$$= \frac{jp^3kLL_2(\sqrt{L_2})(\mu\sqrt{L} - k\sqrt{L_2})}{R^2 + p^2L_2^2} \quad . \quad . \quad (22)$$

From these expressions it is seen that as k or L_2 is increased the real component of aerial impedance due to reaction becomes at first increasingly negative, so that the effective aerial resistance is reduced and may reach the oscillation point; for still further increase in k or L_2 the real reaction component becomes positive and the reaction circuit forms a load on the aerial.

As L_2 changes, the reactive reaction component changes, at first increasing the effective aerial inductance and afterwards decreasing it.

In the practical application of reaction the effective aerial resistance is decreased, with consequent reduction of the aerial damping coefficient; at the same time the effective inductance is increased, so that if the aerial is tuned by condenser variation the damping is further decreased by the increase of inductance, but if the aerial is tuned by variometer the increased inductance due to reaction is neutralized in the tuning.

A moderate degree of reaction is legitimately and properly used to increase the sharpness of tuning when receiving faint or long-distance telephony; by sharper tuning the selectivity of the receiving set and the ratio of tuned signal to interfering noise, and signals on slightly different wave-lengths, is increased. If, however, the reaction is taken too far the curve of aerial current against frequency for constant applied voltage becomes sharply peaked, and the range of frequencies corresponding to the signal no longer lies on a sensibly flat part of the resonance curve, so that there is frequency distortion; this is exactly similar to the result obtained when sharply tuned radio-telegraph receivers are used for the reception of telephony on long wave-lengths. The general principles of oscillatory circuits examined in the first part of this paper also show that abrupt variations in the applied voltage will not be faithfully followed by the aerial current if the damping is made very low, but instead the aerial will set up a damped train of oscillations at its natural frequency at each transient change, and these when rectified appear as noise.

It is hardly necessary to comment on the excessive and incompetent use of reaction that is so common and causes so much interference; the resulting distortion of both kinds referred to above becomes very marked indeed and, in addition, the tuning is generally not exact as is shown by the heterodyne note, so that the upper and lower side bands are not symmetrically reproduced, with results that have been studied and described by R. V. L. Hartley.*

When reaction is applied to a single-valve demodulator, the results are substantially the same as in the case of the radio-frequency amplifier already described. The output from the valve consists of an audio-frequency component and a radio-frequency component; these are separated and the latter is fed to the reaction coil. In respect of the radio-frequency currents in the secondary circuit the valve operates in the same way as the amplifier previously described.

It is not possible to discuss here the many kinds of receiving circuit that are in use with and without reaction, but the application of the general principles given in this paper will generally be sufficient to reveal the conditions required for obtaining good quality in any circuit. There is, however, one type of circuit that uses a distinctive feature, on which a few words must be said. The type referred to is that originated by Armstrong, in which high reaction is used together with a quenching device that prevents continuous oscillation. Such a circuit is a valuable one for long-distance commercial communication, but cannot under any circumstances be considered as a high-quality receiving system, because the high reaction introduces the frequency distortion already described, and the periodic quenching of free oscillations introduces slight noise due to the audible components of the damped trains of waves.

Attempts are occasionally made to apply the principle of reaction to audio-frequency amplifiers. It may be said at once that no important developments are to be looked for along these lines.

It is shown in an Appendix that only a highly idealized resistance-coupled amplifier can have a truly flat frequency-distortion characteristic; in general, the characteristic of a speech amplifier falls away markedly at very low and very high audio frequencies, these frequencies in a good amplifier being outside the range to be transmitted. If reaction is applied, the departure of the characteristic from the ideal flat curve will become more marked, in just the same way as the tuning curve of an aerial becomes more peaked by the application of radio-frequency reaction. If, on the other hand, we suppose reaction applied to an ideal resistance-coupled amplifier, we have an amplifier inherently of rather low efficiency, and reaction will raise the efficiency. In practice, however, the capacity of the valve electrodes and the capacity and inductance of the apparatus prevent the realization of a flat characteristic, with the result that deterioration of the characteristic sets in directly reaction is applied to any useful extent; meanwhile the same improvement in efficiency can be secured with less harmful effect on the characteristic by the substitution of transformer coupling or inductance and condenser coupling. The practical application of reaction to audio-frequency amplifiers is beset with many other complications arising from the curvature of the grid-voltage/plate-current characteristic, which makes the amplifier unstable so that a strong signal may send it into an unresponsive condition.

Dual Amplification or Reflex Circuits.

Like reaction, a method of increasing the output of a single valve that is now coming into prominence is the use of dual amplification, that is the use of a single valve first for radio-frequency amplification and then for audio-frequency amplification. It is, in general, not satisfactory from the point of view of high quality to use a single valve for two different functions, because the circuit conditions that suit one condition of use

* See Bibliography (28).

are generally incorrect for another condition. In dual amplification the vacuum tube operates as an amplifier in both its functions, but the radio and audio frequencies have to be separated by condensers, which cause appreciable distortion in the audio-frequency circuit.

RECEIVERS.

Of the various types of apparatus that have been used for the final conversion of electric current to speech we shall confine our attention to electromagnetic devices, since these are by far the most commonly used.

Where crystal sets or amplifiers of low power having good characteristics are used with head receivers, it is commonly agreed that excellent quality can be obtained; the naturalness also is probably good, but the conditions of listening are such as to make the judgment of naturalness difficult. There are, however, differences observable in the naturalness of different head receivers, caused by differences in the natural frequency of the mechanism and, more particularly, differences in the degree of damping. Owing to the necessity of using mechanical resonance in order to secure an instrument of reasonable efficiency, receivers are less than critically damped; a good receiver, for example, may have a response to a suddenly-applied steady voltage similar to the curves $\beta = 500$ in Figs. 2 and 3, and the distortion inherent in resonant systems occurs.

In order to obtain a satisfactory compromise between efficiency and faithfulness, it has been necessary to make a careful study of the desirable vibration constants of a receiver, taking into consideration the increased damping of the receiver when it is held to the ear. The general theory by which the vibration constants are studied has been described by the author elsewhere.* For many years the design of receivers was based on experimental work with trial and error. The data accumulated by this method, together with Dr. Kennelly's methods of impedance analysis and modern research,† have placed receiver design on a sound scientific basis, to which strong testimony is borne by the fact that the first receiver designed by the new methods had an acoustic power output about $2\frac{1}{2}$ times greater than previous receivers for the same power input, although it was actually smaller and lighter. These improvements in design accompanied the study of telephone-speech quality, with the result that both frequency distortion and amplitude distortion were reduced.

LOUD-SPEAKING RECEIVERS.

Of all the transformations to which the speech or music is submitted in its passage from the source to the listener, the final transformation into acoustic waves by a loud-speaking receiver is the least satisfactory. No loud-speaker has yet been made that sounds perfectly natural, although by proper design and extreme care in manufacture it is possible to secure results that are highly satisfactory, and in fact the intelligibility may be made commensurate with the intelligibility of a head receiver; it is in speech naturalness and musical faithfulness that the principal improvements are to be looked for. Present achievements owe their success to the rather generous tolerance of the human ear* and cannot be said to mark the final development of loud-speaking apparatus.

* See Bibliography (38). † *Ibid.* (40, 42 and 43).

There are very many types of loud-speaking receivers on the market, and the diversities in their faithfulness of reproduction are about as numerous as their types. Some account of the difficulties of securing faithfulness and of the inherent disadvantages of certain types has been given by the author and others at a recent joint meeting of the Institution and the London Physical Society.†

It is not always realized that the receiver mechanism will not handle more than a certain amount of power without serious amplitude distortion; in this respect the receiver should handle as much electrical speech power without distortion as the valve which precedes it. Both valve and receiver must, however, be capable of dealing with the maximum peak voltages occurring, whether due to a peaky wave-form or to the varying intensity occurring pre-eminently in music. Measurements with the cathode-ray oscillograph have shown that the momentary ratio in a short time-interval of peak voltage to R.M.S. voltage for fairly rapid speech collected by a high-quality transmitter is about 6 or 7. A somewhat similar average figure was found for gramophone music, but the music varied in intensity up to a maximum of over 6 times the average intensity for the whole record. These figures are, of course, subject to variation and amendment, but they indicate that a given valve and loud-speaking receiver will only reproduce music without bad distortion on loud notes at an average intensity considerably lower than that at which they can reproduce speech satisfactorily. It is also apparent that in estimating the permissible variation of grid potential from any data obtained by measurement of the R.M.S. value of speech currents, an amplitude factor must be used to provide for the high peakiness of the wave-form.

As a very rough approximation, it may be stated that a good loud-speaking receiver may require from 0·0003 to 0·0005 apparent watt in order to give out speech at a convenient volume level in a moderate-size living room; the apparent watts are supposed measured by the product of mean-squared current and effective resistance (at 800 periods per second) of the receiver. Allowing that the peaks of the voltage wave are 7 times the R.M.S. value, it is easy to calculate that a valve of moderate power is required to give a good performance with speech, while a further margin is required to take care of the wide variation of intensity in music.

In regard to the receiver itself, the current through the receiver is very unlikely to respond well to the steep peaks in the voltage curve, on account of the inductance of the windings; this is, of course, the electrical equivalent of mass in a mechanical system, so that the inductance of the receiver circuit should be kept low relatively to the resistance as well as the mass of the moving parts. Naturally a receiver requires inductive windings, but the effective inductance under working conditions plays no useful part and is analogous

* See Bibliography (5 and 6). † See page 265.

to the leakage flux and magnetization inductance of a transformer; a 100 per cent efficient receiver need have no effective inductance.

The limited amount of power that some receivers are capable of handling is the cause of a certain amount of dissatisfaction, even though the reproduction may be faithful within the power limits of the receiver. The variation of intensity of music between the extreme of pianissimo and the extreme of forte with a full orchestra has been estimated to be an energy ratio of $1:10^7$. It is, therefore, easy to see that if a receiver is incapable of producing as much acoustical energy without distortion as the maximum music intensity to be transmitted, the performance must be heard at a subnormal volume level; under such conditions the pianissimo passages, only just audible in the original music, may be lost altogether in the reproduction, and the ear distortion caused by reproduction at the wrong loudness level will be present. Receivers can be made that will handle the requisite amount of energy to give normal volume reproduction of loud music, but the smaller and simpler types of instrument must not be expected to do it.

It may be assumed that a receiver can be designed to give a required output without amplitude distortion, and that it is used in conjunction with an amplifier of adequate capacity as judged by its freedom from amplitude distortion in handling the peaks of the alternating wave-form applied to the last grid. We then come face to face with the problem of frequency distortion, which in loud-speaking receivers is the most serious problem of high-quality radio-telephony. With ordinary care, and by comparatively easy means, the distortion of all the other apparatus used in radio-telephony can be brought down to reasonably small dimensions; in the loud-speaking receiver such an equally near approach to perfection is still possible, but not as yet at a commercial cost. As the author has pointed out elsewhere (*loc. cit.*) electromagnetic receivers can only be made of sufficiently high efficiency to enable them to be used with moderately-powered valves by employing mechanical resonance; it is by the sparing use of resonance, entailing perhaps the sacrifice of a certain amount of volume efficiency, that high quality has at present to be secured. It is therefore a corollary that the greater the amount of distortionless speech power that the loud-speaker amplifier can deliver, the less resonance need be used in the receiver and the better its quality can be. It is a further corollary that the receiver should be designed in conjunction with the amplifier in order that the combination may give the best results.

Some recent studies on four types of loud-speaking receiver brought into view some interesting facts bearing on the relation between speech quality and naturalness. It was found that the four receivers were approximately equal in speech quality, although they differed widely in naturalness, the same voice being produced with fair naturalness by two of the types, and with an unearthly hollowness and drumminess by the other two types. Investigation showed that the drummy effect was caused by the fact that the receivers in question had natural frequencies at about 650 periods per second, some 200 p.p.s. or more below the resonant frequencies of the more natural receivers. The low-pitched and relatively undamped resonances had little effect upon the intelligibility but had a great effect upon the naturalness.

Noise and Interference.

A consideration of quality would not be complete without some reference to noise and interference, although these factors fall somewhat outside considerations of distortion.

It has been ascertained, so far as speech goes, that the intelligibility of reception depends upon the ratio of noise intensity to speech intensity. The noise to be considered consists of atmospherics, interference from wireless stations or power circuits, valve and amplifier noises (sometimes caused by vibration) and also of the frequencies manufactured by amplitude distortion in the wireless apparatus.

At the present time very little can be done to reduce noise (other than distortion noise) in circumstances where it is serious. High selectivity of the receiving apparatus naturally tends to reduce the noise received when it is spread over a spectrum of wave-lengths; the use of a coil aerial may by its directional effect also enable the ratio of signal to noise to be raised. Other devices have been described from time to time, the object being often to eliminate one particular wireless signal on a wave-length near to that being received; such devices may consist of an auxiliary tuned aerial or various special circuit arrangements. Naturally these devices do not eliminate the extra frequencies due to amplitude distortion.

Conclusion.

In conclusion the author desires to express his indebtedness to his colleague, Mr. W. L. McPherson, for reading the manuscript and for much valuable advice.

Acknowledgments are also due to the Western Electric Company, Ltd., for permitting the results of work carried out in their laboratories to be published.

APPENDIX 1.

The Response-Frequency Characteristic as a Criterion of Quality in Respect of Transient Impressed Forces.

Of the two fundamental types of distortion under steady-state conditions, the frequency distortion is, in general, the more important and more difficult to avoid.

The quality of reproduction of an amplifier (or other piece of apparatus) is commonly examined by plotting the output (voltage or current) for constant input against frequency; such a curve is called the frequency-distortion, or response-frequency characteristic. The ordinates of this curve can be regarded as mutual admittances, or a similar quantity according to the definition of input and output adopted for the purpose of obtaining the characteristic. The phase of the

ordinates is not usually determined, so that it is the modulus of the admittance that is plotted.

In the light of the evidence that the ear will disregard phase differences in the steady state, and the suggestion that it cannot form an image of the original transient disturbance from a phase-distorted reproduction of it, the question arises whether the frequency-distortion characteristic should also show the phase distortion, in order to give a complete representation of the effect of the system on quality.

From the analytic point of view, we must confine our attention to "ironless mathematics," and suppose that our mutual factor relating input and output is formed by addition, multiplication and division of a number of simple factors of the form $\alpha + \beta d/dt$. For the steady state the mutual factor will then take the form $P + jQ$, where P and Q are rational real fractional functions of the frequency p. The modulus will be a polynomial fraction in integral powers of p with a finite number of terms.

The question is whether the modulus, i.e. $\sqrt{(P^2 + Q^2)}$, which forms the ordinary frequency-distortion characteristic, determines uniquely the phase distortion, or whether there can be a number of different functions of frequency having the same plot of modulus against frequency but different plots of phase angle against frequency, that is, different values of Q/P.

We may suppose that the full expression of the mutual factor is $(F_1 + jF_2)/F$, where F, F_1, F_2 are rational polynomials in powers of p. The modulus is $\sqrt{(F_1^2 + F_2^2)}/F$, but is only known as

$$\sqrt{(A + Bp^2 + Cp^4 \ldots p^{2n})}/F$$

The problem is therefore to determine whether $M = (A + Bp^2 + Cp^4 + \ldots p^{2n})$ can be expressed as the sum of the squares of two rational polynomials in more ways than one.

$$\left.\begin{array}{l}\text{Let } F_1 = a_0 + a_2p^2 + a_4p^4 \ldots a_np^n \\ F_2 = b_1 p + b_3p^3 + \ldots b_{n-1}p^{n-1}\end{array}\right\} \quad . \quad (1)$$

Then on squaring F_1 and F_2, adding them together and equating to M, an identity is obtained which furnishes $(n + 1)$ equations to determine the $(n + 1)$ coefficients $a_0 \ldots a_n$, $b_1 \ldots b_n$. Hence F_1 and F_2 can be uniquely determined and the phase angle is

$$\text{arc tan} = F_2/F_1 \quad . \quad . \quad . \quad . \quad . \quad (2)$$

It is seen, therefore, that the plot of the modulus of the mutual factor of any physical system defines also the phase angle of the mutual factor, provided the modulus is expressible as a fraction in integral powers of p.

Since the modulus of the mutual factor defines the phase distortion implicitly, it is evident that transient phenomena need not be studied separately but can be regarded as included in all investigations applied to steady-state distortion; it must be appreciated, however, that the transient distortion is only included in the sense that a good steady-state response characteristic indicates good transient response in a general way, and this is the justification for forming an opinion of the quality of apparatus from its steady-state characteristics.

It would lead too far to investigate the relation between frequency distortion and phase distortion taking into consideration the hysteresis effects of iron-cored apparatus; under such conditions the ordinary expansion theorem for the calculation of transients no longer applies, nor in general is the mutual factor expressible in integral powers of p.

APPENDIX 2.

No invariable amplifier or reproducing mechanism having dissipation can have a frequency characteristic that is perfectly flat in any finite part without being flat from zero to infinite frequency, that is, without having a perfectly constant ratio of reproduction for all frequencies.

The square of the modulus of the steady-state mutual factor for a physical system having a finite number of degrees of freedom and built up of single-valued impedance operators is a rational fraction, finite for all real values of the variable. Therefore, if the variable p be given a generalized complex significance, the square of the modulus of the mutual factor regarded as a function of the complex variable is a holomorphic function in a region as narrow as we please but containing and extending along the real axis. It is a property of such functions that they cannot be constant over a finite interval without being constant everywhere in the holomorphic region. It follows that under the conditions assumed for analytical purposes the enunciation above is verified.

Hence, for example, an idealized resistance-coupled amplifier will have a constant ratio of reproduction for all frequencies, but a transformer-coupled amplifier being necessarily inefficient at very low frequencies cannot have a characteristic that is truly flat in any part, although in practice the characteristic may be experimentally indistinguishable from a straight line over a wide range of frequencies.

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Discussion before the Wireless Section, 7 May, 1924.

Sir Richard Paget: So far as the observations which I have made by ear are concerned, they agree with everything that the author says as to the nature of speech sounds. As to whether aperiodic sounds are really involved: all the sounds, including all the transitions of the transient sounds, appear to be essentially musical. The only possible exceptions are the sounds of "f" (the unvoiced sound) and "th." There is, to the ear, a component—not the main component—which is what may be described as a faint roar. It is an unstable sound which may be truly aperiodic. In practically all the others (I am speaking of consonants as well as of vowels) the components are all essentially musical. As to naturalness, it might be interesting to point out that, in a bass or baritone voice, the larynx frequencies often fall to as low as 50 or 60 per second. For instance, if I say "Oh, oh" my voice has gone through a phase of this sort—861 to 966 and down to a frequency of about 54, i.e. an octave above the lowest note on the piano. Therefore in order to get true naturalness in reproducing a man's voice the apparatus must reproduce frequencies down to the order of 50 or so; otherwise the natural effect of the voice is lost. Music demands a still larger range, because some instruments operate down to 20 vibrations per second. On the upper limit I should say that apparatus would have to respond at well over 5 000 periods to obtain naturalness. The sounds of "f," "th" and "s" all have components of that order; the "s" sound in my own voice has a frequency of between 6 000 and 7 000. The natural frequency of the cavity of the ear may have a bearing on this subject. In my own case it is about 2 900. If one puts a finger into one's ear and then takes it out gradually one hears a note which rises up to about this frequency as the air cavity is completely opened. If the ear is covered with one hand so as to lower its frequency all sorts of external noises are increased by resonance, but as one comes to the natural frequency of the ear these resonant noises cease altogether, indicating that the ear has ceased to be sensitive to noises of the natural external ear frequency. If instruments could be made to have the same natural frequency as the human ear we might be less conscious of their natural periodicity. The intelligibility of different consonants varies greatly, merely as tested by their range in air. I recently made some experiments which may be of interest. The sound of "f" under those conditions had a range of about 40 yards. Under the same conditions "th" had a range of about 80 yards. Above 40 yards "f" was constantly mistaken for "th." Above 80 yards "th" was mistaken for "s." The "s" sound itself was always clearly heard up to 150 yards. But the sound which had much the greatest carrying power was "sh." That is why we use "sh" when we wish to get silence in a hubbub. A word as to the distinction between different transients. I do not think it is necessary to rely on phase differences. I should think it likely that the ear is as unconscious of phase differences in the transients as it is in the case of persistent sounds. The following has to be remembered in regard to every transient sound. Take the "k" and "t" and "b" and "p" sounds. Each of these has several components—always two or three—and each of those components may be moving in a different direction. Thus the middle component may be kept fairly level while the upper one is going up and the lower one is going down; so that although we may start with three similar components, we can get two entirely different transient sounds, because the different components are moving in different directions, or their

amplitudes are increasing in different proportions. For example, the essential differences between the sounds of "p" and "b," and "t" and "d," and "k" and "g" are, broadly, that in "p" and "b" what we hear is simply a variation of amplitude only; there are no audible changes of resonance. In fact, any method by which the resonances are suddenly started or stopped gives the ear the impression of a "p" or "b" sound. D. C. Miller actually made his group of organ pipes say "papa" by simply turning on the air supply sharply twice in succession. There, of course, the resonances were started suddenly and stopped suddenly. The sounds "k" and "g" and "t" and "d" are quite different. They are essentially due to changes of amplitude and of frequency. In "k" and "g" the most remarkable characteristic is that the sound starts by a double release, like turning on a tap in two stages; whereas in "t" and "d" it is by a one-stage release. The high-frequency components of the sound are also much more pronounced in "t" and "d" than they are in "k" and "g." Figs. 5, 6 and 7 in the paper indicate the inadequacy of the system referred to for dealing with low frequencies. It will be seen that if the curves in Fig. 6 are continued back, there would be no amplification at all at 50 periods, and if the curve in Fig. 7 were continued there would again be an amplification, at 50 periods, of only about one-half that obtained over a very wide range from about 400 to 3 000 periods. A few days ago I listened to the loud-speakers at Wembley and I was particularly struck by the fact that no low frequencies at all were audible. There were some very persistent frequencies due to resonance of the horn or the diaphragm. The intelligibility was good. To sum up: for naturalness in music and in male voices we undoubtedly need responses to frequencies of from 20 to 50 and upwards. For intelligibility we want a greater sensitiveness in the higher regions, from 5 000, I should say, up to about 7 000. Some very interesting experiments on the duration of human speech sounds have recently been published by Mr. Jefferson of the Phonetic Laboratory at University College. The device which he used enabled the actual movements of the jaw to be recorded. From that, exact information could be got as to the actual times occupied by syllables in human speech.

Captain B. S. Cohen: On page 792 there are references to intelligibility, articulation, and traffic efficiency. Intelligibility and articulation are defined in this country very much as the author has defined them; but traffic efficiency has not been considered to any great extent and I do not think that the term will find very much favour. I suggest in its place some such term as "transmission speed factor." That would prevent any confusion with the normally-accepted definition of "traffic." I am glad that the author emphasizes (on page 793) the necessity for reproducing at about the same volume level, as it has been frequently stated that a perfect repeater on a much reduced volume scale is all that is required, and this conception results in unsatisfactory reproduction. On page 796, under the heading of "Measurement of Intelligibility," the author refers to lists of monosyllables for determining the proportion of syllables accurately recorded, and states that the lists are arranged to give equal weighting to the different elemental speech sounds. In this country it is customary to weight these lists in the proportion of the frequency of occurrence of the various speech sounds in average speech. Some occur very much more frequently than others and it is considered better to weight these lists than to take an equal weighting for each elemental speech sound. On page 798 the author refers to five types of high-quality transmitter in use at present. I should like to refer to three other types which it is considered may be of very considerable value for radio-telephony reproduction, but which are at present being utilized principally for measurement purposes. The first is the eddy-current transmitter due to Mr. Hewlett, who terms it a "tone generator." This consists of two rigid slab coils placed close together, with a thin disc of aluminium foil between. This disc of foil can be moved to and fro by impinging sound waves which pass through spaces in the coils. The eddy currents produced in the aluminium foil by the field from the slab coils through which a polarizing current circulates are utilized for reproduction. This gives very faithful reproduction and there are no resonance points over the audio range. The second form is merely a loose-leaf condenser of a few sheets used as an aperiodic transmitter. This offers considerable possibilities and is one of the earliest forms of condenser transmitter. The third form is the Wollaston wire thermophone. The footnote on page 799 states that standard cable has an attenuation constant of 0·109 per mile. This is, however, an obsolescent American standard, and the standard in this country and a number of other European countries has an attenuation constant of 0·106 per mile. With regard to transformer-coupled audio-frequency amplifiers, I propose to exhibit lantern slides showing curves similar to those obtained by the American Bureau of Standards. These have been obtained with apparatus which was demonstrated at a recent meeting of this Institution and are actual reproductions of the photographic curves obtained on an oscillator outfit used for the measurement of frequency-amplitude characteristics. The two sets of curves shown indicate the results obtained with two types of intervalve transformers. There are four curves for each transformer, indicating the variations obtained with reversal of primary and secondary windings. These curves demonstrate the importance of the self-capacity of the windings. Although one of these sets of curves indicates a high-quality article, the other set, obtained with an expensive type of transformer, is decidedly unsatisfactory and indicates a very small percentage of output below 350 periods and above 3 500 periods. I agree with the author that it is somewhat amazing to the telephone engineer to see how unsatisfactorily such results compare with those obtained in ordinary telephony repeatering.

Mr. L. B. Turner: I wish to refer first to transients, of which frequent mention is made in the paper; and secondly to the parasitic frequencies introduced at the demodulator. Hitherto, telephonic theory has rather desperately idealized and vastly simplified its problems in assuming steady-state conditions. The author points out that such conditions are not a close approximation

to facts, and boldly attempts to utilize steady-state analysis to give at least qualitative guidance in respect to transients. I think that the importance of the transient treatment is even greater than the author suggests. Not only must consonants admittedly be so treated, but also clearly vowel sounds whose duration in constant strength is brief; and it seems at least very doubtful whether even steady vowel-like sounds can be expressed as a Fourier series. In a recent issue of *Nature* (26th April, 1924), Prof. E. W. Scripture refers to this matter as follows: "The analysis of a vowel into component tones can be shown to be mathematically and physically impossible . . . The Helmholtz theory that vowel sounds are composed of tones harmonic to the voice tone . . . pushed aside the Willis theory that the vowels consist of independent vibrations aroused by puffs from the larynx. . . . After years of oblivion, the Willis theory has been shown to be true for German vowels by Hermann, and for English vowels by myself." That merely adds force to the author's insistence on the importance of transients. Now what does he do with transients? In Appendix 1 it is proved that "transient phenomena need not be studied separately but can be regarded as included in all investigations applied to steady-state distortion"; but it appears to me a *non sequitur* to deduce that "a good steady-state response characteristic indicates good transient response in a general way." Transient conditions are proved to be determined when steady-state conditions are determined; but I cannot see that circuits which are good or bad with respect to the steady state are therefore necessarily good or bad with respect to transients. Argument from steady state to transients is difficult and dangerous. On page 805 occurs the phrase, "a phase-distorted reproduction of a transient." What, I would ask, is the meaning of "phase" in a non-periodic disturbance? The author states on page 798 that "it has been shown by Moullin and Turner that for strong signals the demodulation is likely to follow a linear law," but reference to our paper * (Section 11, page 717) will show that the signal at the rectifier would have to exceed some 2V before the square law would be departed from appreciably, and practical signals (in the absence of a local heterodyne oscillator) are, of course, very much less than this. Let us assume, therefore, a rectifier characteristic $i = \alpha + \beta v + \gamma v^2$, and (following the symbols used in the paper) let us consider a carrier wave $B \sin ct$ modulated simultaneously at two acoustic frequencies $p_1/(2\pi)$, $p_2/(2\pi)$ so producing in the rectifier a P.D.

$$v = E + B(1 + A_1 \sin p_1 t + A_2 \sin p_2 t) \sin ct.$$

The rectified current is easily shown to consist of a constant term and 24 sinusoidal terms, of which 18 are of inaudibly high frequencies [e.g. $(2c - p_1 + p_2)/2\pi$] and six of acoustic frequencies. Only these six affect the ear, and they are given in frequency and amplitude in Table A.

Of these terms, a and b are wanted, c and d are not wanted, but being second harmonics of a and b they are not likely to be particularly noxious. Terms e and f, on the other hand, are likely to be troublesome. All the parasitic terms can be reduced to insignificance if the expense of sufficiently reducing the modulation can be faced, or if the carrier wave could be replaced or reinforced by sufficiently powerful local oscillation introduced at the receiver. Of the four parasitic terms $c - f$, which must be present in some degree if both side-bands are radiated, three vanish if the valuable Western Electric Co. single side-band method of transmission * is used. If in our example both the lower side-waves $(c - p_1)$ and $(c - p_2)$ are filtered out before reaching the transmitting aerial, the bracketed terms c, d and e in the table vanish (and the remainder are all halved in amplitude). The fact may lie embedded somewhere in the author's bibliography, but I have nowhere seen any reference to this further good feature of the single side-band method. We are accustomed to hear from the British Broadcasting Company that their transmissions are above criticism, and that if we do not get perfect music we must strive to improve our receivers. But I am not convinced. Might not an improvement perhaps be effected on the lines that I have indicated? In considering such matters, one must not forget that, in broadcasting, the familiar

TABLE A.

Term	Frequency × 2π	Amplitude × $4/\gamma B^2$
a	p_1	$4A_1$
b	p_2	$4A_2$
[c	$2p_1$	A_1^2]
[d	$2p_2$	A_2^2]
[e	$p_1 + p_2$	$2A_1A_2$]
f	$p_1 - p_2$	$2A_1A_2$

economic relation between transmitter and receiver is reversed. In two-station wireless the cost of the receiver is only a very small fraction of that of the transmitter; but in broadcasting, great expense should be undertaken lightly at the transmitter if a small gain may thereby be effected in each of its 100 000 receivers.

Mr. P. W. Willans: I should like to refer to Appendix 1 of the paper, regarding which I am in agreement with the views of the last speaker. Undoubtedly, perfect knowledge of the modulus characteristic of a system would imply perfect knowledge of the phase characteristic, but it does not by any means appear to follow that any degree of uniformity in part of the one implies a corresponding degree of uniformity in the other. A Campbell filter is a sufficiently good instance of the contrary. Within my own experience of low-frequency amplifiers, results obtained over a limited range of frequencies only are most misleading, modulus characteristics of the same general form yielding totally different phase angles at corresponding points. In order to illustrate my meaning I should like to describe some work which we have been carrying out recently at Chelmsford on measurements of low-frequency transformers. Most of these

* *Journal I.E.E.*, 1922, vol. 60, p. 708.

* H. W. NICHOLS: "Transoceanic Wireless Telephony," *Journal I.E.E.*, 1923, vol. 61, p. 812.

have been done on a single stage of voltage amplification and consist of comparisons between the input and output voltages in respect of both amplitude and phase. The input voltage v_g is applied to the grid of a valve (see Fig. A) in the anode circuit of which a transformer is connected, the output voltage v_g' being developed across the secondary of the latter. By means of an audio-frequency bridge method the vector ratio v_g'/v_g could readily be measured at amplitudes corresponding to those experienced in practice. The results obtained were most astonishing to us at the

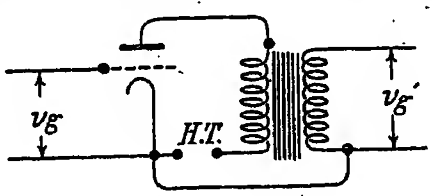

FIG. A.—Single stage of voltage amplification.

v_g = instantaneous input voltage.
v_g' = instantaneous output voltage.

time but have since proved capable of fairly exact interpretation on the basis of simple theory. A pair of curves corresponding to two different transformers is shown in Fig. B. These illustrate the possibility of obtaining over a limited range of frequencies modulus characteristics which are substantially uniform, together with phase characteristics of differing degrees of uniformity. It would be almost impossible from an inspection of the characteristics, as plotted, to deduce that the phase-shift in curve A was double that in curve B over the same extent of characteristic, i.e. between 1 000 and 4 000 cycles per second. In fact, the great degree of uniformity in the characteristic

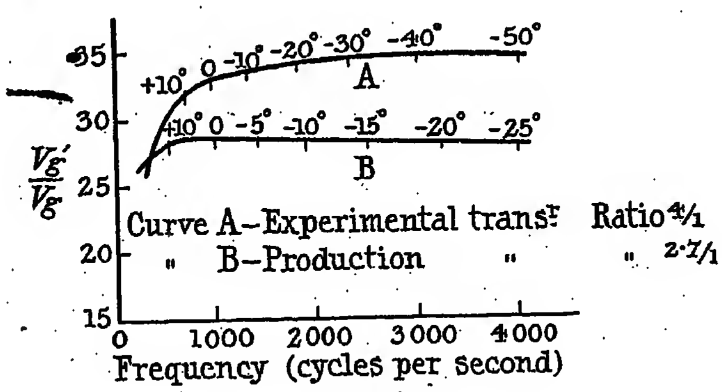

FIG. B.

of curve A might have led to the conclusion that the self-capacity was extremely low and the resonant frequency at about 3 000. The point at which the phase angle is zero, however, indicates that the resonant frequency is about 1 000, and the maintenance of more or less constant amplification at higher frequencies has proved to be due to the magnetic leakage of the transformer. The characteristics exhibited by a previous speaker illustrate the effect of this leakage to an even more marked degree, the abnormal amplifications at high frequencies (which already appear in curve A) being developed into a pronounced resonance hump. This effect would be produced on the transformer of curve A if it were used with a valve of lower internal resistance than that for which the curve was plotted (R type, r = about 45 000 ohms) and it would therefore appear that the curves just exhibited were plotted for valves of lower internal resistance than those for which the transformers were designed. I should like to mention, in passing, with reference to page 800 of the paper, that all intervalve transformers that we have measured which are in any degree efficient exhibit resonance effects well within the audio-frequency range, the phase angle becoming zero at some such frequency. It is not absolutely clear whether the author condemns all transformers exhibiting effects of this kind or only those for which the characteristics

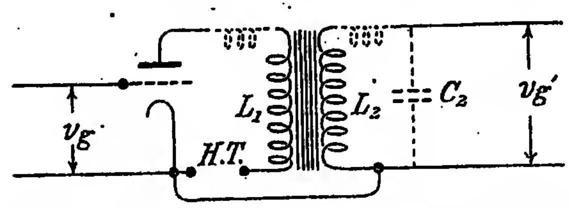

FIG. C.—Effect of magnetic leakage on transformer amplification: diagram of transformer with magnetic leakage and self-capacity in the secondary circuit.

are specially "peaky." Our own experience is that resonance in itself is not only harmless when properly damped by the valve but is practically a necessity if the best results are to be obtained, as otherwise a sacrifice of efficiency on the low notes is entailed. The question of magnetic leakage in intervalve transformers appears to be of the greatest importance. In connection with the theory of this subject I should like to refer to a paper * by Mr. W. L. Casper which certainly deserves a place in the author's bibliography. We had no knowledge of this or any other publication on the subject at the time of carrying out the work which was completed during the course of last year. The theory is interesting, both from the point of view of phase distortion and as accounting for the

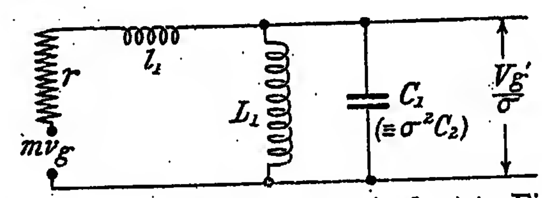

FIG. D.—Simplified circuit equivalent to Fig. C.

m and r = valve constants.
σ = transformer ratio.
l_1 = effective leakage inductance (assumed entirely located in primary).
$C_1(=\sigma^2 C_2)$ capacity introduced into primary by secondary.

abnormalities in the transformer characteristics recently exhibited. Referring to Figs. C and D, the former shows a transformer in circuit having leakage inductance in both its windings and self-capacity in its secondary circuit. The self-capacity of the primary and the resistance of both windings may be neglected. Fig. D shows a simplified equivalent circuit in which the secondary circuit is replaced by a capacity shunted across the primary, equal to the effective self-capacity of the secondary multiplied by the square of the ratio of transformation, and all the leakage inductance is assumed to be located in the primary circuit. The ratio of transformation is not necessarily the ratio of the total number of turns, but nevertheless can, with

* *Journal of the American Institute of Electrical Engineers*, 1924, vol. 43, p. 197.

a fair degree of accuracy, be taken as constant at all frequencies. A study of Fig. D will show the general effects to be expected at different frequencies. At the lowest frequencies the impedance of C_1 will be considerably higher than that of L_1 and the value of the latter will therefore determine the amplification to be obtained. At the resonance of L_1 and C_1 the full valve magnification will be obtained, since the impedance of the parallel resonant circuit may be regarded as infinite in comparison with that of l_1. At frequencies above the resonance of L_1 and C_1 the reactance of the latter will become capacitative and tend to neutralize that of l_1. Ultimately a frequency will be reached at which these reactances cancel each other out and the impedance in the anode circuit of the valve is zero. It will depend on the relative values of the various constants as to whether an increase or decrease of amplification is obtained above the resonant frequency of L_1 and C_1. We may regard this in a somewhat different way. The parallel resonance circuit L_1C_1 is shunted by r; consequently the smaller r is, the more heavily the resonant circuit is damped. On the other hand the resonant circuit l_1C_1 (assuming that the shunting effect of L_1 at this frequency is negligible) is in series with r; as a result, reducing the value of r will make this resonance less damped. If, therefore, we choose a transformer of given ratio and connect with a valve of either very high or very low internal resistance, bad resonance effects will be obtained. The curves recently exhibited give an indication of an exaggerated second resonance, due to the combined effects of an excessive magnetic leakage and a valve of too low internal resistance. With a valve of higher internal resistance a better curve would be obtained at high frequencies, but the "cut-off" at low frequencies would, of course, be more pronounced. The only satisfactory way of avoiding troublesome effects of this kind would appear to be the reduction of the magnetic leakage of the transformer to the utmost extent, and this step has been taken in the design of an intervalve transformer at present in course of production. In considering this leakage it must be borne in mind that the alternating flux densities in the core are so low that only the initial permeability of the iron must be taken as indicating the proportion of the total flux carried by the core. It is thus quite erroneous to assume unity coupling, even if the iron circuit is of excellent design. Transformers in which special attention is given to the reduction of magnetic leakage not only exhibit a greater freedom from distortion over wide ranges of frequency, both in respect of phase and amplitude, but also, owing to the better employment of the valve damping, are more stable in multi-stage amplifiers and will operate more reliably under the slightly varying conditions that are met with in commercial apparatus.

Mr. W. J. Rickets: To reproduce speech correctly it is necessary to give the illusion of a person seated in the studio or central producing room. It is not possible entirely to reproduce the effect because, although it has been proposed, it is exceedingly difficult to produce a stereoscopic or stereophonic effect. It is, however, probably not impossible ultimately to produce sounds of the same quality and intensity as those impinging on the microphone or similar device at the studio or the transmitting station. In all loud-speakers and amplifiers very considerable phase differences as regards components of various frequencies are certainly introduced, and it is yet possible to obtain quite fair results. The ear appears to act as a sort of Frahm frequency meter. If transients were applied to a frequency meter many of the reeds of the meter would probably respond to the sudden jar, whereas if a sustained compound wave is applied it will indicate the particular frequencies that are present. In the same way the ear will probably respond to steady-value sounds which are applied, and all frequencies present will be appreciated irrespective of the phase relationship. It is probable that many consonantal sounds are indicated by the envelopes of the vibratory curves, and not so much by the frequencies that are present. In improved loud-speaker and audio-frequency apparatus the system should respond fairly quickly to any transient changes which are produced. Probably the varying sensibility of the ear to sounds of varying frequencies and amplitudes is the cause of the phenomenon of apparent distortion which can be noticed in the near vicinity of a loud-speaker. The loud-speaker may sound perfectly clear when one faces the front of the trumpet, but, if one moves round laterally, apparently considerable distortions appear. That is probably an effect due to the varying energy radiation along different radii and to the varying sensibility of the ear to the components which are projected. One thing necessary in the production of real naturalness on a large scale is so to arrange the loud-speakers that at any point a person listening shall hear sounds proceeding from one focus. At some demonstrations sounds can reach the listener from two loud-speakers, and by acoustic interference very peculiar effects may be produced. If a large loud-speaker or several loud-speakers are located at one point, probably the sound waves proceeding outward are more or less spherical. The sound which reaches the listener is of one phase, but if more than one loud-speaker is used and the sources of sound are separated it is almost inevitable that some of the component waves arriving from one or other of the loud-speakers are considerably out of phase. This may occur when the individual loud-speakers are giving quite good results. The loud-speaker is sometimes blamed as being a very unsatisfactory device. It is certainly very inefficient from the energy point of view, but when it is considered that all loud-speakers are in effect a multi-frequency single-phase motor coupled to an air pump, which has to operate on current of frequencies varying from about 50 or 60 up to 10 000 per second, and voltages varying in somewhat the same ratio, it is really very wonderful that the results obtained from loud-speakers attached to reasonably good amplifiers are as faithful as they are.

Dr. N. W. McLachlan (*communicated*): The paper is a useful epitome in general analytical form of current knowledge concerning the principal elements which cause distortion in a broadcasting system. There are two omissions, namely, (1) the valve transmitter and its associated circuits, and (2) night effect—including

fading—on distances of 100 miles and upwards. The principles governing faithful reproduction at the transmitter—or more accurately, faithful modulation of the carrier wave—are similar to those at the receiver. Some of these were cited in a lecture which I delivered before the South Midland Centre early last year,* in which the various distorting factors, except night effect, were treated in a simple manner. There are, broadly speaking, two modes of defining distortion: the first is on an artistic basis, whereas the second is on a scientific basis. From an artistic viewpoint, quality must be adjudicated by competent trained musicians or musical critics. The sense of quality in this instance is to a certain extent arbitrary, owing to variations in the aural perceptions of different individuals. From a scientific viewpoint reproduced sounds are undistorted when the fluctuations in air pressure at the microphone and at some suitably situated point in the reproducing room are identical. It might be difficult to fix the proper point, owing to the reaction of the walls, etc. This latter effect could be surmounted in the well-known manner by draping to secure acoustic damping. Strictly speaking, both definitions are inadequate, since the quality depends upon the relative positions of microphone and orchestra or singer. I endorse the author's comments on the distortion accompanying loud-speaker reproduction. The fact that moderate-intensity headphone reception is usually accepted as being of better quality than that of a loud-speaker is probably due to the absence of audible alien tones, since the sounds are relatively weak. On the other hand it would appear—owing to the inherent amplitude and frequency distortion of one's aural mechanism—that there must be aural distortion, since the sounds with telephones are very much weaker than the original. Moreover, it seems that distortion occurs with both loud-speakers and headphones, but the sounds from one are more acceptable than those from the other. It is stated that the reproducer should be arranged to yield the same intensity of sound as that at the studio. The question immediately arises: What point in the studio should be chosen? I expect that the microphone position is intended. Despite distortion due to the reduction in intensity, I think the author would prefer not to hear a military band at full strength in a room of average size. I have listened carefully to the larger types of loud-speaker yielding moderate acoustic intensities, taking care to avoid distortion in the valve circuits. Although accurate measurement is the only safe criterion, I feel that the reproduced version of instrumental music contains tones which are not present in the original. In making comparisons it is well to do so at intervals, because the ear requires a rest of several days to avoid a natural aptitude for becoming increasingly tolerant and optimistic. Assuming my alien-tone diagnosis to be correct, and that such tones do not exist in the modulatory apparatus at the transmitter, it is essential to look to one or more of the sources of asymmetry at the receiver or to impulsing at the reproducer. The various ways in which asymmetry is likely to occur are: (1) Deep modulation of the carrier wave, and the mutual effect of this and the curvature of the rectifier characteristic. The frequencies of the alien tones will depend upon the equation to the rectifier characteristic, and this is not always of parabolic form, which has been assumed. The author states that demodulation will follow a linear law with strong signals. This only holds, however, when the transmitter modulation is not too deep. (2) Operation of valves on the curved portions of their characteristics. In reality only a comparatively small proportion of a characteristic is sensibly linear, and with moderate amplitudes a certain degree of asymmetry is introduced, but this may be sufficiently small to be undetected by the average ear. (3) Improper adjustment of the valves, thus obtaining grid current. For moderately loud sounds, say for an average room, a grid bias of the order of − 18 volts or more is advisable, so that extraordinary maxima do not promote grid current. This means that the valve characteristic should be linear over a range of 36 volts on the grid, i.e. from − 36 to zero grid volts. (4) Hysteretic and saturation effects in iron-cored transformers and in certain types of loud-speaker. Owing to the presence of a polarizing current, the iron operates on a subsidiary and not on a main hysteresis loop. The value of the effective permeability is altering continuously, and its value is the slope of the loop at any instant, i.e. dB/dt. (5) Unbalanced type of reproducer or loud-speaker, in which the force-displacement curve is asymmetrical about the equilibrium position, for example the usual reed or diaphragm class of instrument (not the "Magnavox"). The Gaumont conical-coil type of loud-speaker is also asymmetrical, since the restoring forces on the coil are unequal for the to-and-fro directions of motion, owing to the mechanical construction. (6) Non-linearity of the force-displacement curve of the moving part of the reproducer for large amplitudes. The frequencies of the alien tones in the two latter cases depend upon the curvatures of the force-displacement curves. Lastly there is the influence of the free oscillations of the diaphragm and other parts of the reproducer capable of vibration. During a transient, the reproducing system, consisting of the loud-speaker and its component parts, is impulsed, and imposes its natural frequency and a train of overtones of enharmonic frequencies—with a circular diaphragm there is an exception when it is in two parts *—in varying degree, according to the increment of the transient. The effect of the main free oscillation of the diaphragm can, of course, be curtailed by introducing an acceptor circuit; also a certain degree of damping is exercised by the last valve, which is usually of low impedance. It is probable that the alien tones, to which reference has been made, were associated with causes (4) and (5), and with free oscillations of the loud-speaker assemblage. The faithful reproduction of transients is of

* *Beama*, 1923, vol. 13, pp. 286 and 366; also *Electrician*, 1923, vol. 90, p. 394, and *Wireless World*, 1923, vol. 12, p. 82.

* (1) C. V. RAMAN and S. KUMAR: "Musical Drums with Harmonic Overtones," *Nature*, 1920, vol. 104, p. 500. In this paper a certain type of Indian drum whose overtones are integral multiples of the fundamental is treated. The drum consists of a central circular portion loaded with a special adhesive mixture containing finely divided metal, and an outer supporting ring. (2) R. N. GHOSH: "Musical Drums," *Physical Review*, 1922, vol. 20, ser. 2, p. 526. In this paper the loading of Indian drums is discussed, and it is shown that when the load varies inversely as the square of the distance from the centre, the overtones form a harmonic series, whereas inverse linear loading yields an enharmonic series.

paramount importance, since they form the essential characteristics of either speech or music. The difficulties in accurately reproducing pianoforte transients are well known to those who have studied the subject. The piano is analogous to a spark transmitter with its impulsive effects at the receiver, whereas the violin, 'cello or kindred instrument, during the steady state, is analogous to the carrier wave of a continuous-wave transmitter. In general the initial rates of rise of transients which occur with the violin, etc., are less rapid than those from a percussion instrument like the piano. There is, of course, pizzicato playing on the violin and the beating of drums or clanging of cymbals, also the chiming of large bells, which yield fairly severe transients. As stated in the paper, it is customary to suppose that the phases of the various tones are unimportant during the steady state. I wish to ask the author if this applies to a very complex sound from a full orchestra for all intensities from pianissimo to fortissimo. In treating the topic of transients analytically, he concludes that distortion problems can be regarded in the same class as those during the steady state, but this only applies provided there is no phase-shift. One would expect that with a heavily damped transient, the phases of the resulting spectrum of frequencies into which the transient can be resolved would be of importance in aural interpretation. In this respect the following example of tonality may be of interest: It is known to piano manufacturers that two instruments of similar construction are different in tone. This is said to be due —amongst other things—to the relative intensities of the fundamentals and their partials; also to the phase relationships of these frequencies.* If the latter statement is correct, it is probable that the phases of the component frequencies of a transient play their part in determining the quality of instrumental music and maybe that of speech. Reference is made here to the infinite series of frequencies—within the range of audibility—into which any transient can be resolved. The phases, as well as the amplitudes of the component frequencies, determine the wave-form of the transient. If the phases are of importance in aural interpretation, the relative phases of the air pressures at the studio must be identical with those at some point in the reproducing room. I should be glad if the author would state whether it is possible to secure zero phase-shift throughout a complete radio-telephonic system. It is fairly obvious that the usual type of low-frequency amplifier causes phase-shift. Another example of tonality was brought to my notice owing to the fracture of a copper-loaded string in my pianoforte. A new string was inserted, but beats could never be eliminated from the two strings. An examination of the new string showed that it was loaded with smaller wire than the old one. Although the unisons or fundamentals of the two strings could be tuned, the overtones gave beats, showing that in one or both strings the overtones were not integral multiples of the fundamental. Coming to the other side of the problem, where tones are eliminated in the reproduced version of music, the suppression of the higher tones due to an exalted degree of reaction can be readily demonstrated when reproducing the violin. The instrument then yields comparatively pure tones and simulates the flute, which is not rich in upper partials.

Mr. L. C. Pocock (*in reply*): Sir Richard Paget questions whether aperiodic phenomena are really involved in speech, since he finds that all the transitional sounds are essentially musical in character. I think that this is true; one might say that Nature abhors sudden changes, such as the elemental transient force that I have dealt with in Equations (4), (5) and (6), and it certainly seems that the only way of producing such a severe transient change is the detonation of a small cap or bomb; other sounds such as the drawing of a cork, which to an ear less acute than Sir Richard Paget's suggest mere noise, are highly damped periodic vibrations and the existence of definite pitch is readily observed when several such sounds are made in succession under conditions which give each one a different pitch. For clearness of thought it may be advisable to distinguish between tones which can be resolved into continuous pure tones, and those which are periodic only in the sense that the pressure and velocity are zero at equally spaced intervals of time. Both classes of disturbance may be grouped together under the title of "cisoidal oscillations" applied to them by G. A. Campbell.* It seems evident that as far as aural analysis goes there can be no sharp distinction between steady tones and periodic tones in which the amplitude is changing, for the rate of change of amplitude may be so small that a damped tone (e.g. that produced by a tuning fork) sounds pure; if the value of the damping at which overtones appear is at all critical it may reasonably be expected to be associated with the phenomenon of masking.† The sounds of a third class characterized by continuous change of time between successive pressure zeros characterize certain consonants and the clang of a bell ‡: these have no periodic structure whatever.

The point which I have tried to emphasize is that telephony has developed on a mathematical basis of steady-state vibrations, whereas every change of amplitude and frequency introduces foreign transient responses which depend entirely on the response of the system to the elementary transient dealt with in Equations (4) to (6).

I am obliged to Captain Cohen for pointing out an objection to the use of the term "traffic efficiency" for associating with the intelligibility of the transmission system the time taken to convey an idea. His alternative suggestion, however, appears open to the criticism that although it may not have been already appropriated for that purpose it certainly suggests the reciprocal of the wave-length constant (imaginary part of the propagation constant). I would therefore suggest some such term as "conversation efficiency" or "communication efficiency." I cannot agree that the monosyllables used in articulation-testing should be weighted according to the frequency of occurrence of the sounds in English;

* C. V. Raman: "Partial Tones of Bowed Strings," *Philosophical Magazine*, 1919, vol. 38, p. 573. In addition to the treatment of partial tones obtained by bowing a string at nodal and other points, the question of the phases of these tones is discussed.

* *Journal of the American Institute of Electrical Engineers*, 1911, vol. 30, p. 873.

† See Bibliography (2).

‡ *Ibid.* (21b).

to do this is to attempt to measure something between intelligibility and articulation as I have defined it. As a fundamental principle it is better that experimental observations should aim at the determination of the inherent properties of the matter investigated, with the exclusion of as many incidental variables as possible, in order that the results may possess a broad application. In this case, articulation is the property of the system to reproduce sounds closely similar to the original sounds; if all pronounceable sounds are used with equal weighting the tests measure this property in its simplest form. Measurements thus made have the widest possible significance, and the conversion of articulation percentages to intelligibility percentages can be made for any language from the same basic results. This point of view is worth consideration in connection with the rapid strides now being made towards a higher development of international telephony.

In reference to Mr. Turner's allusions to the nature of vowel sounds, it will probably be agreed that a complete explanation has yet to be presented. The fixed-pitch theory of vowels is not sufficient to enable vowels to be constructed; it is noteworthy that synthetic vowels have been produced only by means of vibrations rich in overtones (probably enharmonic) and it seems to me that the reinforced enharmonic partials on each side of the characteristic vowel tones are essential to vowel character, but whether these owe their origin to independent puffs or not does not appear to me to have been conclusively proved. The meaning of my reference to phase distortion in a transient is as follows: There are two ways of regarding a Fourier integral: (1) as a mere indentity, a function which states the value of any arbitrarily selected ordinate, and (2) as a continuous spectrum of simultaneously existing frequencies. The former view is brought out in Heaviside's treatment * and the latter in Byerley's "Fourier Series and Spherical Harmonics." If the Fourier integral is regarded as a spectrum of frequencies each element has its appropriate phase which is determinable [see Bibliography (28) for an example], and it is to the initial phase of these partial waves that I refer.

The particular advantage of single side-band transmission referred to by Mr. Turner is mentioned briefly by R. V. L. Hartley.†

A very important criticism by Mr. Turner bears upon the relation between the perfection of transient reproduction and the perfection of steady-state reproduction. The difficulty in establishing any relation lies in the fact that only a moderately successful judgment of the faithfulness of reproduction can be made from an inspection of the response-frequency characteristic; if the curve lies evenly between fairly narrow limits over a sufficiently wide range of frequency, reproduction will be good, and if it has excessive humps and hollows, or is not approximately constant over a sufficient range of frequency, the reproduction will be poor; but of two curves both showing frequency distortion it is not possible to say by inspection which is the better unless one obviously approximates to the good type and the other obviously falls in the other category. With the same degree of approximation it may be argued that an ideal response-frequency curve (constant for all frequencies) indicates that discontinuities, and therefore transients, will be accurately reproduced, while a bad response-frequency curve showing excessive humps and hollows indicates inferior transient reproduction characterized by parasitic oscillations depending upon the elements of the system. It is clear that the ideal characteristic for steady-state reproduction is the same as the ideal characteristic for transient reproduction, but any further comparison is rendered difficult by the absence of means of determining the effect upon aural interpretation of alterations in the shape of the response characteristic. It can, however, be shown that the duration of an *oscillatory* response to an impulsively applied force diminishes as the response characteristic grows flatter (the general shape of the curve, that is the frequencies at which maxima and minima occur, being kept unchanged). It is also possible to deduce from the work of J. R. Carson * that in a low-pass filter the response to an impulsive impressed force becomes less sluggish as the cut-off frequency is raised. In these cases, therefore, transient and steady-state reproduction improve concurrently.

Mr. Willans appears to attach considerable importance to the phase characteristics of transformers, because he adopts zero phase angle as the definition of resonance. There are various ways of defining resonance in parallel circuits† and care must be taken to adopt the appropriate definition when, as in transformers, the resistance term is important. In this case maximum current through L_1 of Mr. Willans's Fig. D is the appropriate definition of resonance, because the frequency at which this occurs will give a maximum on the frequency-response curve. When there is appreciable magnetic leakage, the resonance conditions of a circuit simplified even as in Fig. D are complicated and the zero phase frequency has not in general a critical significance. A careful analysis of the transformer equations will be found in the bibliography.‡ I should like to point out that a transformer should be designed to work between certain impedances and should be tested between those impedances; if a valve is used it should be the right valve and the already complicated theory of transformers need not therefore be further complicated by considering the effect of using wrong impedances.

Dr. McLachlan, referring to the aural distortion arising from reproduction at the wrong loudness level, suggests that such distortion is preferable to the hearing of a military band at full strength in a small room. The latter is not the meaning I intended to convey; the intensity of reproduction in a small room should not be the same as that of a band playing in the room, but rather the intensity at which the band is intended to be heard, for example, at a distance of 20 or 30 yards in an open park, and it is indirectly to produce open-air conditions that a studio should be heavily damped for the reproduction of band music. I am inclined to think that the phase of tones in the very complex sounds of a full orchestra is practically as unimportant as

* "Electromagnetic Theory," vol. 2, par. 271.

† See Bibliography (28), p. 41.

* "Transient Oscillations," *Journal of the American Institute of Electrical Engineers*, 1919, vol. 38, p. 345.

† Bibliography (44), pp. 78 and 79.

‡ Item (46).

among two or three tones; the various instruments will never be all in phase as heard at a given point, nor will their overtones be in phase; if a large number of instruments were in phase on a single tone a secondary effect, viz. aural amplitude distortion, might occur simply on account of the unduly high intensity of the note, but the resulting increase in harmonic overtones would scarcely be important. According to D. C. Miller the total loudness of two distinct tones is independent of their relative phase, and this is reasonably consistent with the theory of the mechanism of hearing. I am glad to find that Dr. McLachlan agrees with me that phase distortion of the components of a transient are important, but when I say that the reproduction of transients is determined by the steady-state characteristics I include this effect for the reason that, in circuits capable of analytical treatment, the transient reproduction is wholly determined by the mutual factor, which in turn is uniquely determined by the frequency characteristic.

BENEVOLENT FUND.

26TH ANNUAL GENERAL MEETING, 8 MAY, 1924.

(Held in the Institution Lecture Theatre.)

Dr. Alexander Russell, F.R.S., President, took the chair at 5.30 p.m.

The notice convening the meeting was taken as read.

The minutes of the 25th Annual General Meeting held on the 31st May, 1923, were taken as read and were confirmed and signed.

The Report of the Committee of Management (see below) and the Statement of Accounts for the year 1923 (see page 542) were presented and, on the motion of the Chairman, seconded by Captain R. J. Wallis-Jones, were unanimously adopted.

Mr. J. Attfield, F.C.A., was unanimously re-elected Hon. Auditor.

The Chairman reported that the following Committee of Management had been appointed for 1924–25 :—

The President (*ex officio*)
Sir James Devonshire, K.B.E. } Representing
Captain J. M. Donaldson, M.C. } the Council;
Lieut.-Colonel K. Edgcumbe }
Mr. S. W. Melsom } Representing
Mr. W. R. Rawlings } the Council;
Mr. A. A. Campbell Swinton, F.R.S. }
Mr. S. Evershed } Representing
Captain R. J. Wallis-Jones } the
Mr. P. Rosling } Contributors;

and the Chairman of each Local Centre in Great Britain and Ireland.

The meeting then terminated.

[Prior to the Annual General Meeting an Extraordinary General Meeting of the Contributors to the Fund was held for the purpose of confirming the new Rules for the furtherance of the object of the Fund, which had been approved at an Extraordinary General Meeting held on the 27th March, 1924.]

REPORT OF THE COMMITTEE OF MANAGEMENT FOR THE YEAR 1923.

CAPITAL.

The Capital Account stood on 31st December, 1923, at £9 969 11s. 3d.

RECEIPTS.

The Income for 1923 from dividends, interest, and annual subscriptions was as follows :—

	£	s.	d.
Dividends on investments	470	12	9
Interest	9	3	9
311 annual subscriptions	231	1	6
	£710	18	0

In addition to the foregoing, the Fund benefited during the year by the following donations, many of which are non-recurring :—

	£	s.	d.
Electrical Engineers' Ball Committee	63	0	0
W. T. Henley's Telegraph Works, Ltd.	25	0	0
"Twenty-Five" Club	15	15	0
Messrs. Mullard and Graham	15	0	0
R. N. Vyvyan	14	10	0
Incorporated Municipal Electrical Association	10	10	0
F. R. Marsh	10	0	0
and 593 non-recurring donations of under £10	251	13	7
	£405	8	7

The accumulated balance of the Income and Expenditure Account amounted on 31st December, 1923, to

£1 622 17s. 6d., of which £1 002 19s. 3d. was invested, and £500 on deposit with the Institution bankers.

Donors and Subscribers.

Lists of the names of donors and subscribers during 1923 have been published in the *Journal*.

The Committee of Management desire to acknowledge their indebtedness to the donors and subscribers. As will be seen from the Accounts, the Expenditure practically equals the Income, and the Committee venture to urge upon members the pressing need for a generous support of the Fund. Apart from donations, the Committee will be grateful for annual subscriptions even of small amounts.

Grants.

Applications for assistance were made by, or on behalf of, 24 persons during 1923, and the Committee, after due consideration, made grants in 21 cases.

The total amount of the grants was £1 034 2s. 4d.

Wilde Fund.

The Capital Account stood on the 31st December, 1923, at £2 798 10s. 2d., of which £2 797 18s. 1d. is invested and brings in an annual income of £99 11s. 10d.

The balance standing to the credit of the Income Account, from which, under the Trust Deed, full Members only can benefit, on the same date was £182 9s. 7d.

No grant from this Fund was made during the year.

INSTITUTION NOTES.

International Conference on E.H.T. Supply Systems.

The Third Conference [see *Institution Notes*, 1923, vol. 61, pp. (5) and (9), and *Journal I.E.E.*, 1924, vol. 62, p. 132] will be held at Paris about the end of June, 1925. As in the case of the previous Conferences held in 1921 and 1923, discussions will take place in French and English on Reports presented by members of the Conference. Visits to works and excursions will also be arranged. Full particulars can be obtained from the General Secretary of the Conference, M. Tribot-Laspière, 25 Boulevard Malesherbes, Paris.

The Benevolent Fund.

The following is a list of the Donations received during the period 26 July–25 August, 1924:—

	£	s.	d.
Burgum, W. T. (Minas Geraes, Brazil)	1	0	0
Cox, P. H. (Cheltenham)		3	6
Grey, W. J. (Shanghai)	1	5	0
Griffin, J. G. (Hatfield)		10	6
Horowitz, H. (London)		5	0
Lacey, H. M. (London)	1	0	0
Lane, W. E. (London)		5	0
Naylor, W. S. (Manchester)	1	1	0
Oliphant, T. (Shanghai)		10	0
Thomas, A. O. (Sarawak)		6	0
Whitehorn, H. K. (Maidstone)		2	6

Accessions to the Reference Library.

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4to. 353 pp. *London*, 1924

Ashford, C. E. Electricity and magnetism: theoretical and practical. 3rd ed.
sm. 8vo. 315 pp. *London*, [1922]

Atkins, E. A. Electric arc and oxy-acetylene welding.
sm. 8vo. 323 pp. *London*, 1923

Atkins, W. Common battery telephony simplified. 4th ed.
8vo. 139 pp. *London*, 1921

Baines, A. E. Germination in its electrical aspect. Together with some further studies in electro-physiology.
8vo. 205 pp. *London*, 1921

—— Studies in electro-physiology (animal and vegetable).
8vo. 320 pp. *London*, 1918

Baker, R. P. Engineering education. Essays for English selected and edited by R. P. B.
sm. 8vo. 194 pp. *New York*, 1919

Bangay, R. D. The elementary principles of wireless telegraphy. [2nd ed.].
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Bowker, W. R. Electrical circuits and connections. A technical, practical, and operative treatise on direct, alternating, polyphase, and hydro-electrical engineering circuits. Being the 3rd enlarged edition of "Dynamo, motor and switchboard circuits for electrical engineers."
8vo. 223 pp. *London*, 1922

Broughton, H. H. The electrical handling of materials. A manual on the design, construction and application of cranes, conveyors, hoists and elevators. 4 vols.
4to. *London*, 1920–23

1, Electrical equipment.
2, Structural work.
3, Electric cranes.
4, Machinery and methods.

Brown, S. E. Experimental electricity and magnetism.
sm. 8vo. 228 pp. *Cambridge*, 1922

Brownlie, D. Mechanical stoking.
sm. 8vo. 244 pp. *London*, 1923

Campbell, L. L. Galvanomagnetic and thermo-magnetic effects. The Hall and allied phenomena.
8vo. 323 pp. *London*, 1923

Case, J. The theory of direct-current dynamos and motors.
8vo. 209 pp. *Cambridge*, 1921

POWER CIRCUIT INTERFERENCE WITH TELEGRAPHS AND TELEPHONES.

By S. C. Bartholomew, Member.

(*Paper first received 28th January, and in final form 10th March,* 1924; *read before* The Institution 10*th April and before the* Mersey and North Wales (Liverpool) Centre 28*th April,* 1924.)

Summary.

The subject is of interest to the designer, the power engineer and the communication engineer, and the time appears to be ripe for a review of the situation. The paper is a general survey of the position, describing the features in the modern generation and distribution of electrical energy which are responsible for interference with telegraph and telephone circuits, emphasizing the importance of harmonics in this connection, and indicating some known remedies which may be applied to power plant at its source when trouble is experienced.

The improvements to be expected by the transposition of wires forming overhead power and telephone circuits are described and also the practical applications. The separating distance and length where power lines and communication circuits run parallel is next considered with reference to inductive effects from (*a*) the balanced voltages and currents, (*b*) the residual voltages and currents, and (*c*) the abnormal occurrences due to short-circuits, etc.

The balance of telephone circuits is then dealt with. Telephone circuits in this country are designed to be free from disturbance from telegraph circuits and telephone circuits carried on the same routes. It is considered that a balance which will ensure this is the most that can be expected in such a system as a public telephone service, and if disturbance from power circuits is experienced with such balanced conditions on the telephone circuits, then the injurious affection is excessive. Remedies which may be applied to telephone and telegraph circuits are described.

A review of the problem and general experience in this country is then given under the headings of tramways, railways (direct-current and single-phase), and electric light and power systems, with an account of certain remedies and a discussion of the lay-out of power systems as influencing interference. In the author's opinion the solution of the inductive problem is mainly one for the designer; the power engineer, the telephone engineer and the protective-gear engineer are also concerned in that order.

In an appendix Prof. E. W. Marchant describes a method of removing ripples from mercury-arc rectifiers.

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Introduction.

The object of the author in presenting this paper is to provide an opportunity for the different interests concerned to discuss the subject on a common platform, with a confident assurance that nothing but good can result from such a course. Mr. Frank Gill in his Inaugural Address* for the Session 1922–23 made a pointed reference to this matter, and the time appears to be opportune for ventilating a subject which is of importance to the designer and the power engineer as well as to the telegraph and telephone engineer. In passing it may be pointed out that a great part of the general public may be interested in the problem, especially by the effects on land lines used for wireless simultaneous broadcasting.

The greater telephone development and the different conditions as regards the generation and transmission of electricity in the United States have resulted in the problems associated with interference developing earlier, and apparently in a much more violent form, than in this country. This is very evident from the widespread interest in the subject in that country, which has culminated in the appointment of Joint Committees of the National Electric Light Association and Bell Telephone Systems on the physical relations between the electricity supply and signal systems. The National Main Committee consists of 56 members, and there are local committees covering districts and sub-committees on research, field investigations, etc.

* *Journal I.E.E.*, 1923, vol. 61, p. 1.

All those interested in the subject are indebted to the Railway Commission of the State of California for publishing the results of the exhaustive tests carried out by the Joint Committee on Inductive Interference appointed by that body. The technical and other reports are included in a publication of 1 200 pages which gives an indication of the thoroughness with which the investigations were carried out. The treatment of the subject from both the scientific and practical standpoints is of a very high order. It does not deal, however, with the electric traction side of the problem.

In this country we have not had the same widespread problems. The troubles have been more in the nature of isolated incidents, and the need for research on anything like the scale found necessary in America has not arisen. This can partly be explained by the fact that until the last few years there was little distribution of electrical energy by overhead lines, the development being almost wholly underground. Further, where high-pressure and extra-high-pressure lines have been erected, cross-country routes have been the rule, and in few cases are the routes parallel with and in close proximity to the main trunk lines of the Post Office which follow the public roads. In America, it is gathered, it is common practice for the power transmission lines to be erected on public roads, whilst the voltages employed appear to be generally higher than in this country where 33 kV is the highest in use at the moment, although a 66-kV line is under construction.

In presenting the paper the author asks for a certain amount of tolerance from the power engineer and designer for presenting some features of their work in an elementary manner, having in mind the telegraph and telephone engineer; and on the other hand he asks for consideration from the latter in regard to any explanations which may appear unnecessary but which may perhaps be helpful to the power engineer and designer.

It is not claimed that the matter presented is new or the treatment original. A great deal of the technical information is contained in standard textbooks and in papers contributed to various Institutions, but hitherto the salient points bearing on the subject have not been easily available to anyone desiring to make himself acquainted with them.

It is proposed to use the words "communication circuit" to cover both telephone and telegraph circuits, except in cases where the particular type of circuit requires special treatment, and as a preliminary it will be well to consider what is involved by each of those methods of communication.

The technical problem of telephony is concerned with:

(a) The transformation of the spoken word into electrical waves corresponding to it;

(b) The transmission of these electrical waves for perhaps hundreds of miles with the least possible distortion or loss of intensity and without the addition of foreign disturbances; and

(c) The reproduction at the receiving end of an audible sound which is a counterpart of the electrical wave and so of the originating spoken word.

The apparatus employed in this interplay of sound waves and electrical waves is extremely sensitive and delicate, dealing as it does with amounts of energy so small as to be outside the ordinary purview of the power engineer. A telephone receiver will respond to a fraction of a microwatt, i.e. that amount of power will transform an electrical wave into an audible sound wave.

Similarly, telegraph systems, although not so sensitive as telephones, have to reproduce faithfully the originating electric impulse as a signal at the receiving end of the circuit. Here again the apparatus is very delicate and the operating currents are small.

It is obvious from this that if the telephone and telegraphs are to carry out their functions in an efficient manner they must be kept free from foreign currents and voltages, which are relatively infinitesimal compared with the strong currents and voltages employed on power systems.

The working of power systems may have detrimental effects on telegraph and telephone systems by leakage or by induction.

Definition of leakage.—Leakage currents are those which stray from a power system and enter a communication circuit at an earth plate and leave it at another earth connection on the same circuit. Telegraph circuits are usually worked with an earth return, and such circuits are more likely to be affected by leakage from stray currents than are telephone circuits.

Stray currents may emanate from tramway or railway systems using an uninsulated return, or from faulty electric light and power circuits. The strength of a stray current depends upon the voltage between the two earth connections and the resistance in the circuit.

The communication-circuit apparatus may be made unreliable or useless according to the strength of the stray current in the circuit.

Definition of induction.—Inductive effects from power circuits may interfere with the working of telegraph circuits by mutilating the signals, and in the case of telephone circuits may affect the signalling arrangements associated with calling and clearing or, what is more common, disturb the speech on the circuit by producing noises.

Inductive interference with communication circuits may be caused either by the normal operation of the power circuits or by abnormal conditions resulting from short-circuits, switching operations, etc. Further, in certain circumstances, even though the working of the circuits may not be affected, conditions may be set up by induction producing such high potentials in the communication circuit that there is actual danger to life from shock or risk of damage to plant.

With the effects described there is also a danger of acoustic shock to anyone who might happen to be listening on a neighbouring telephone circuit at the time. As regards danger to life, it should not be taken that such conditions exist or have existed in this country.

Inductive interference may be produced by both overhead and underground power circuits, the former being the more usual. It is, of course, unnecessary to discuss here the general laws of the inductive effects of

electrostatic and electromagnetic fields associated with electric circuits, as, with the exception perhaps of electrolytic and heating work, they are associated with every useful application of electricity. The author thinks, however, that it will be helpful to recall briefly the principal features.

Electromagnetic induction.—The strength of a magnetic field round a conductor is directly proportional to the current. If the current is alternating there is a complete cycle of change in the field with every cycle of current. The rate of change of the field intensity is proportional to the frequency, being influenced to a certain extent by the wave-shape. The density of the magnetic field is greatest near the conductor, and at other points varies inversely as the distance from the centre of the conductor. The induced voltage produced by a power line upon a neighbouring wire running parallel with it will depend upon the field strength (which is proportional to the current), the frequency, the length of parallelism and the separating distance.

Electrostatic induction.—Where wires are suspended in the air and insulated from each other and the earth, they may be regarded as two plates of a condenser. Each wire forms one side of the condenser, the earth being the other. Any charge or electromotive force applied to one wire will produce a difference of potential between that wire and the ground, which will affect the potential between the other wires and the ground. With every change of strength in the electromotive force, or with reversals such as are associated with alternating-current systems, the charges induced in the wires will vary accordingly. The electric charge on a wire varies directly with the applied voltage on the disturbing wire. The potential of this charge will depend upon the capacities of this wire to the disturbing wire and to earth. The charging current produced depends upon the value of this potential and on the capacities referred to. It follows from this that while the charging current and therefore the disturbance vary as the length of parallelism, the static potential induced is not affected by the length. The charging current varies also with the frequency. As the electrostatic induction on a conductor depends not only upon the capacity between the conductor and the disturbing wire but also upon the capacity between the conductor and earth, it follows that the presence of other wires and earthed objects in the neighbourhood affects the conditions in this respect.

The following is a comparison of the effects of the two fields:—

Electrostatic induction is proportional to the voltage of the power system but is independent of the current, whilst electromagnetic induction varies with the current in the power system but is unaffected by the voltage. Both electrostatic and electromagnetic effects are proportional to the frequency of the power system. Where power lines and communication circuits are in such proximity that inductive interference may be expected, this is usually referred to as an "exposure." The voltages produced by electrostatic induction are independent of the length of the exposure, whilst the electromagnetic effects are proportional to the length of the exposure. On the other hand, the amount of current flowing is in both cases approximately proportional to the length of the exposure, the current due to magnetic induction being the same at all parts of the circuit, which is not the case with that due to electrostatic induction.

A study of inductive interference in America, the principal work on which has been carried out by the Californian Railway Commission previously referred to, has led to the standardization of terms which are very convenient for describing the conditions associated with the problem. Power-circuit voltages and currents are classified under two general heads: (1) Balanced voltages and currents, and (2) residual voltages and currents, the former being those which are balanced with reference to the earth, whilst the latter are those which are unbalanced with respect to earth. At any instant of time, the algebraic sum of either the balanced currents or the balanced voltages in the several conductors is zero, whilst the algebraic sum of the total currents in the several conductors is the residual current, and the algebraic sum of the total voltages to earth is the residual voltage. As an illustration, a circuit consisting of an overhead trolley wire with an uninsulated rail return is wholly unbalanced with respect to the earth, the total voltage and current being residual. On the other hand, a double-wire circuit with no connection to earth and conductors arranged symmetrically with respect to the earth and other objects would have neither residual voltage nor current, as the voltage to earth on one side would be equal and opposite to that on the other. The same would apply to the current, and in that case both voltages and currents are wholly balanced.

Excepting the cases of traction systems employing earthed returns, it can be taken that the balanced voltages and currents are those which perform useful work in the circuit, whilst the residuals perform no useful part in the operation of the system and are, in fact, a measure of the failure to reach a perfect design in the apparatus and line, having in mind other interests.

The inductive effects of "residuals" are usually greater than those produced by "balanced" voltages and currents of equal magnitude. This is due to the fact that the residual components in the several conductors are all in phase and their inductive effects are cumulative, whilst the balanced components in the several conductors are out of phase. For instance, in the case of a three-phase system they are out of phase by 120°, and the resulting effect is materially influenced by the fact that the balanced components partially neutralize one another. In other words, the residual voltages and currents act like a single-phase circuit consisting of the line conductors in parallel, and an earth return. Inductive effects are therefore relatively great, as there is little neutralizing as is the case with balanced voltages and currents.

The causes of, and remedies for, these inductive effects will be indicated in the sections dealing with the different power systems, but it will not be out of place to point out here the salient differences between the two kinds of inductive effects.

Residual currents and voltages act as though the power system were a single-phase system with the line

conductors in parallel, and transpositions or crosses in the power lines do not reduce the inductive effects, except in so far as such a proceeding brings about a reduction in the magnitude of the residuals themselves; for instance, the line capacities may be brought into better balance thereby. On the other hand, transposing or revolving the wires forming a telephone circuit disturbed by such inductive effects will reduce the interference.

In the case of disturbance due to balanced currents and voltages, transposing or revolving both power lines and telephone wires will reduce the inductive effects.

Residual currents and voltages may be produced in the power system by the following conditions:—

(*a*) Unbalanced capacity and leakage between the various conductors and earth.

(*b*) Unbalanced loads between phases on a system in which the neutral point is earthed.

(*c*) The development of the third harmonic and its odd multiples in generators and transformers on systems using star connections with the neutral point earthed.

As regards (*a*), it is obvious that to reduce these the various conductors must be arranged uniformly, relative to earth or other bodies. Similarly, (*b*) is a matter which can be taken care of by a proper lay-out of the system and its loads.

In the case of (*c*), the remedy lies in the design of an alternator to generate voltages and currents as nearly as possible of sine wave-shape, and in the employment of transformers working with a small magnetizing current and so connected that the effects of hysteresis and changing inductance in disturbing the wave-shape of current and voltage curves are minimized. These and other measures for reducing the troubles under this heading are treated fully in the section dealing with harmonics.

It is important to note that the presence of large residual currents is possible only where there are earth connections on the power circuits, as if earth connections are not used the residual currents are limited to leakage currents and unbalanced charging currents. It should here be pointed out that in this country one earthed connection only is allowed on each distinct circuit, with the exception of electric railways and tramway systems using uninsulated rail returns, and in some special cases, such as the interconnection of large power systems referred to later.

The inductive effects of the different types of power circuits as used commercially will be dealt with under their respective heads: Traction (Railways and Tramways) and Electric Light and Power, but there are certain common features which affect the intensity of disturbance and which may be summarized as follows:—

Avoidance of close proximity between power wires and communication circuits.—This is the only sure way of preventing disturbance.

The use of apparatus (rotating machinery and transformers) designed or worked in such a way as to be free from harmonics.—The bulk of inductive interference with telephones is due to harmonics.

Restriction of residual voltages and currents.—These are particularly difficult to lessen in the case of traction systems using track returns. In the case of ordinary power systems, they can be lessened by line balance, by the avoidance of excessive magnetic density in transformers, by avoidance of certain transformer connections, and in some cases by the provision of supplementary devices which suppress or short-circuit the harmonic components. These effects are not reduced by transposing the power lines, except in so far as such transposing assists in equalizing the capacities of the conductors to earth.

Transposing the power line conductors.—This will reduce the possibility of inductive effects due to balanced voltages and currents.

Transposing the communication circuit conductors.—This will reduce the effects of residuals and balanced voltages and currents. It applies more particularly to telephone circuits which are, with very few exceptions, equipped with two conductors. Telegraph circuits, on the other hand, are, with few exceptions, one-conductor circuits with earth returns, and hence cannot be transposed.

Electrical balance of communication circuits.—This is important. A telephone circuit with its two conductors and apparatus perfectly balanced as regards series impedances, capacities and leakage to earth, and with both conductors exposed uniformly to the inductive effects, would be free from disturbance. Unfortunately, such ideal conditions cannot be obtained in practice. The varying weather, trees, the small boy with the stone, are factors which would defeat the most skilful balancing of the terminal apparatus, even if it were commercially possible to provide apparatus balanced to fulfil laboratory requirements. Circuits in underground cables are, of course, not included in the above list of disabilities.

Abnormal conditions on power systems.—These may cause disturbance of a very serious character in neighbouring communication circuits, even if they are not of long duration.

Noise in Telephone Circuits.

To appreciate the effect of small currents in producing noise in telephone circuits, it should be borne in mind that a small fraction of a microwatt of power at voice frequencies will produce an audible sound in a telephone receiver. The frequencies of voice currents in a telephone circuit are found to vary between 100 and 4 000 cycles per second. This last figure may seem a high one, but it should be borne in mind that we are dealing with the currents produced by the overtones as well as the fundamental pitch of the human voice (the pitch of male singing-voices usually falls within the frequencies 80 to 500 per second, and of female voices between 160 to 700 per second). The mean frequency of these varying currents is found to be 800 per second, which is the figure used for telephone transmission calculations.

Any extraneous currents in a telephone circuit having frequencies within the limits mentioned will therefore have deleterious effects on the efficiency of a circuit, and this is particularly the case with extraneous cur-

rents of frequencies between 800 and 1 200 cycles per second. Mr. Gill in his Inaugural Address* gave a curve illustrating the relative interfering effect of single-frequency currents in a telephone receiver. The matter is dealt with at length also in a paper† by H. S. Osborne. For reference, Mr. Gill's curve is reproduced in Fig. 1 of the present paper. It is based on a number of observations with various listeners. It is obvious that the interference effects of foreign currents are influenced very greatly by the frequency. The effects of an extraneous current at a frequency of 25 cycles per second is about 1/1 000th of that produced by current of the same strength at a frequency of 1 100 cycles per second. As bearing on the same point, Lord Rayleigh stated that the maximum sensitivity of the ear is reached at not less than 1 024 vibrations per second and possibly higher (see *Philosophical Magazine*, 1907, vol. 14, p. 602).

Power circuits do not usually operate at a higher fundamental frequency than 60 cycles per second, and

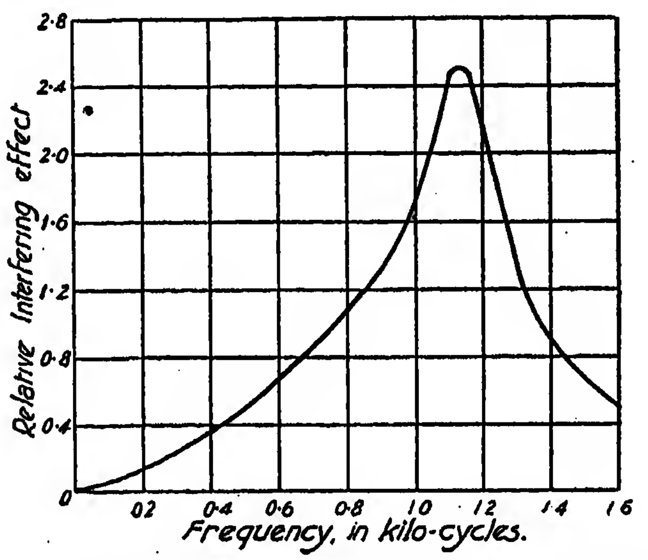


FIG. 1.—Relative interfering effect of single-frequency currents in a telephone receiver.

there is little interference with speech from the fundamental frequency. It is unfortunate, however, that there are usually present, due to various causes, harmonics on the fundamental voltage or current wave which are within the range of the human voice, and it is these harmonics which are the chief cause of interference with telephone circuits.

If the current and voltage waves of power systems were of pure sine wave-shape there would be little or no disturbance of speech in neighbouring telephone circuits, as, apart from the less sensitivity of the ear mentioned above, the telephone receiver itself is not so responsive to these low fundamental frequencies. It is possible, however, for the fundamental frequency to interfere with the telephone apparatus used for signalling, etc., and also with telegraph circuits.

The effect of the higher harmonics is to produce noises in the telephone receiver, which, even if they do not prevent good speech, are always annoying. In cases where the amount of noise is not sufficient to distract the attention of the telephone user, it may interfere with the effective use of the circuit by reducing intelligibility, and so decrease the value of the circuits.

It is possible to operate a telephone circuit which has a good margin of speech efficiency, even though there may be considerable interference, but it will be realized also that with a circuit working near the limits of commercial speech the introduction of a disturbing effect may be sufficient to render the circuit unworkable.

The telephone system of the British Post Office is laid out on a system of definite speech-transmission values, the unit fixing the values being "miles of standard cable," that is equivalent audibility to that received over a circuit of a definite length with standard apparatus for transmission and reception. The standard cable is one having conductors of 20 lb. per mile, and constants of capacity, inductance, etc., which need not be gone into here. Suffice it to say that measurements of audibility are made in terms of standard miles in the same way that pounds and yards are used for measurements of weight and distance. The allowances for audibility vary with the type of service given. Local service should not exceed 30 m.s.c. (miles of standard cable), whilst the general standard for long-distance communication between Great Britain and Ireland aims at a transmission audibility not exceeding 35 m.s.c. between any two subscribers. It should perhaps be observed that the greater the number of m.s.c., the less is the audibility; further, that although 35 m.s.c. is regarded as the standard of good commercial speech, expert telephone users can receive with much higher figures. It will be seen, therefore, that speech values are the basis on which line plant is provided. The saving of an additional mile of standard cable may involve very great cost, and similarly the addition of interfering noise reducing audibility may be represented by monetary loss. As an example, on a 600-lb. aerial trunk circuit 200 miles long, the loss of one mile of standard cable reduces the circuit to that of a 400-lb. circuit, and if a 400-lb. circuit would suffice, then 35 tons of copper would be saved.

The amount of noise that can be tolerated on a telephone circuit without undue interference with speech has not been specially investigated by the Post Office. In one or two cases of interference, measurements have been made of the amount of loss in miles of standard cable introduced by the inductive effects; this method involves comparative audibility measurements being made with the power circuit in operation and when shut down, but the arrangement is not satisfactory unless the interfering noise is considerable.

Two other methods, more suitable for general application, are, however, under investigation.

The apparatus for the first (see Fig. 2) consists of an alternator giving a sine-wave of known frequency and output, and of means for listening to the sound produced by known fractions of this. This known sound is balanced against the induction which it is desired to measure, by the two being rapidly interchanged by means of a commutator, the whole arrangement forming a kind of "flicker" sound meter. A similar kind of arrangement, using relays to change over, has been

* *Loc. cit.*
† "Review of Work of Sub-Committee on Wave-Shape Standard of the Standards Committee," *Transactions of the American Institute of Electrical Engineers*, 1919, vol. 38, p. 261.

used in America for comparing pure sounds of different pitch. A commutator has the advantage that the speed of change-over and duration of the different times of contact are more definite and can be easily reproduced. Precautions must be taken to screen the various parts of the apparatus against spurious induc-

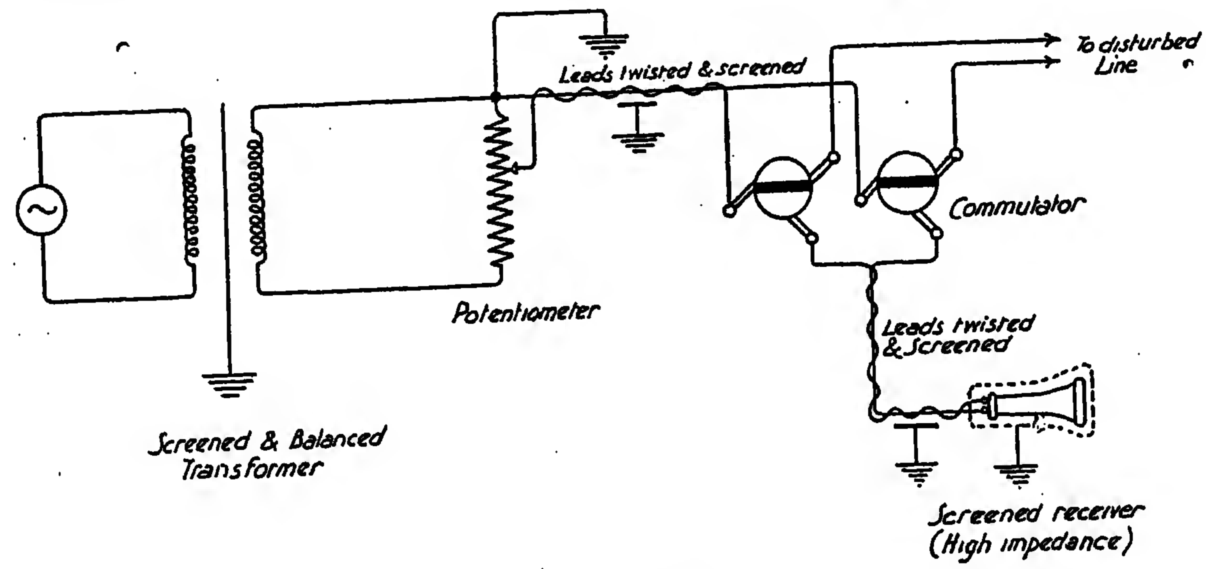


FIG. 2.—Circuit for quantitative measurement of line induction.

tion, and the impedance of the receiver used must be of such a high value as not to upset the line or disturbance under investigation. It is advisable to make tests with two different receivers, one being non-resonant and giving the absolute disturbance, and the other of

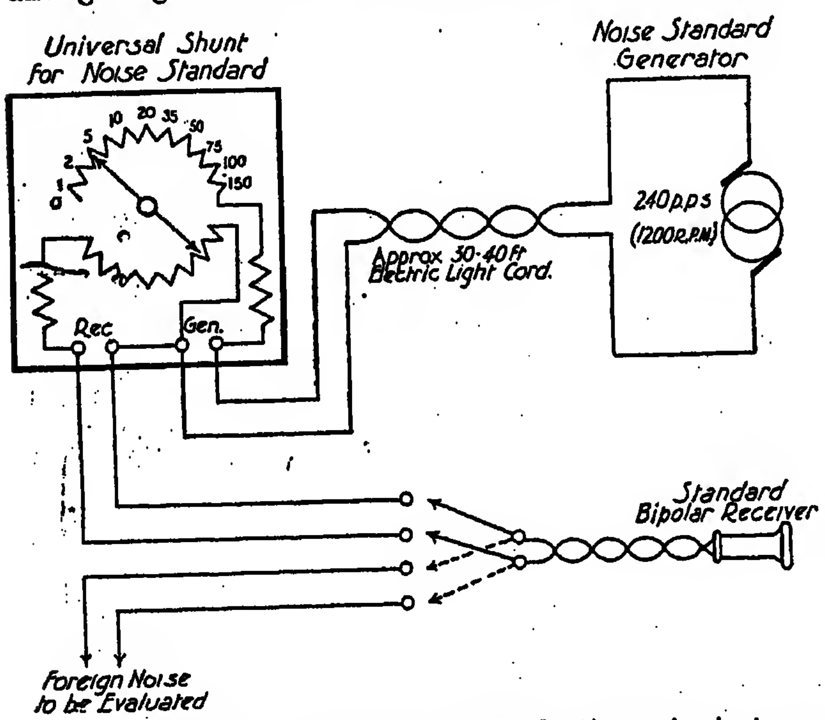


FIG. 3.—Noise-standard circuit for evaluating noise in terms of noise units.

normal type with a resonance point round about 1 000, which will give a measure of the effect that may be expected on a subscriber's instrument. This method enables the induction of practically any character of audible frequency to be directly compared with a standard, though arbitrary, sound, and hence a comparison may be made of the induction found at different times, in different places and of different character.

The second method consists in magnifying by an amplifier the induction up to any convenient value in a circuit containing a potentiometer, the current in which can be measured on any suitable a.c. milliammeter. The line induction is then compared directly with a fraction of the amplified current and can hence be given as a voltage. A great disadvantage of this method is that it is difficult to ensure that the current measured is due only to that producing audible induction. The use of "up" and "down" filters is necessary to cut out all but the audible range, and this involves additional complication. The voltage values obtained from different inductions will not be a definite measure of their relative powers of causing disturbance unless they are caused by currents of the same frequency and wave-form.

In America a standard noise-measuring circuit has been devised, and the arrangement is illustrated in Fig. 3. The method involves the comparison with a standard noise of the induced current in the telephone receiver, the magnitude of the standard noise being changed until the two noises, standard and induced, are judged by the observer to have the same detrimental effect on a telephone conversation. The generator which produces the standard noise is connected to a shunt box by means of which various amounts of standard current are shunted through a telephone receiver. The telephone receiver is connected alternately by means of a mercury switch to the standard noise shunt and to the line under test, and the magnitude of the standard noise is adjusted by means of the shunt until the point of equality is found.

The standard-noise generator is an electric generator of the inductor type, composed of a disc of non-magnetic material in which are inserted a number of soft iron pole-pieces and which revolves between the poles of a permanent magnet. Coils are wound on the poles of the magnet and, as the disc revolves, an alternating current is induced in the winding by the pulsations of the magnetism caused by the motion of the soft iron pole-pieces under the permanent magnet. The voltage of the generator and the resistance of the shunt are so adjusted that when the generator is operated at 240 cycles the calibrations on the shunt give directly

the effective value of the current through the telephone receiver in micro-amperes. In the standard apparatus this shunt is provided with steps up to 150 μA. It is stated that this amount is not sufficient in certain cases, and that as the variations in quality and pitch of the interfering note differ considerably from that of the standard, it is somewhat a matter of individual judgment as to the valuation of the standard noise, and the method cannot hope to be precise. Men who are accustomed to measuring noise, however, usually agree as to magnitude. It is this difficulty which it is hoped to avoid in the apparatus now under investigation. The author does not know the number of noise units which is considered unobjectionable in America, although it has there been suggested as a basis that, as regards important circuits of such length that the speech margin is small, the extraneously induced current in the telephone circuit should not exceed in noise-producing value the effect of 10 μA at a frequency of 240 cycles per second. On unimportant circuits and where there is a surplus of volume of transmission, as on short-distance circuits, current somewhat in excess of the above limit could be allowed. These proposals do not appear to have been agreed as acceptable, however, to the two interests concerned.

There are difficulties in the way of fixing a maximum allowable noise. Any public telephone circuit in this country is likely to be joined through to any other, wherever situated, and should it happen that the various circuits in the series making up the completed connection—local, junction, and trunks—has each its maximum noise, the cumulative effect might be disastrous. Each circuit taken alone might be tolerable, but in combination is unfit for public service.

Harmonics.

It is generally found in power systems that high-frequency components are present in the current and voltage waves. In the case of alternating-current systems these high-frequency components are usually a multiple of the fundamental frequency and are called harmonics. Similar components are often found in direct-current systems, and it is usual to refer to these also as harmonics. Harmonics perform no useful purpose in the operation of the power system and may, in fact, in certain circumstances have deleterious effects. Generally it can be taken that their removal is advisable in the interests of the power undertaking, apart from the effects that they produce by disturbing telephone circuits.

Harmonic currents and voltages are produced in various ways, and a brief account is given below of their principal causes and some known remedies. The author does not profess to cover the whole ground and must refer those who are more deeply interested to the fuller treatment given in many standard textbooks and papers, some of which are referred to in the bibliography.

In alternating-current systems the principal harmonics in generators are due either to slots or to the shape of the magnetic flux curve, and in the case of transformers to the relationship between the flux and the magnetizing current.

Slot harmonics are produced by practically all generators and motors and are the most frequent cause of disturbance in telephone systems. The conductors on the armatures of generators and motors are placed in slots on the surface of what is practically a revolving cylinder, the projections between the slots being known as teeth. It is the breaks in the surface of the iron at the slots which are the fundamental cause of the harmonics. In all types of generators and motors the greater part of the magnetic flux from the field poles to the armature will pass through the teeth, as there is a smaller air-gap at those points. The amount of the flux entering or leaving the teeth may be taken as being proportional to the toothed surface affected by any particular pole, and as the armature revolves there will be a corresponding change in the strength and in the position of the flux in the air-gap. This is illustrated in Fig. 4, which, in an exaggerated

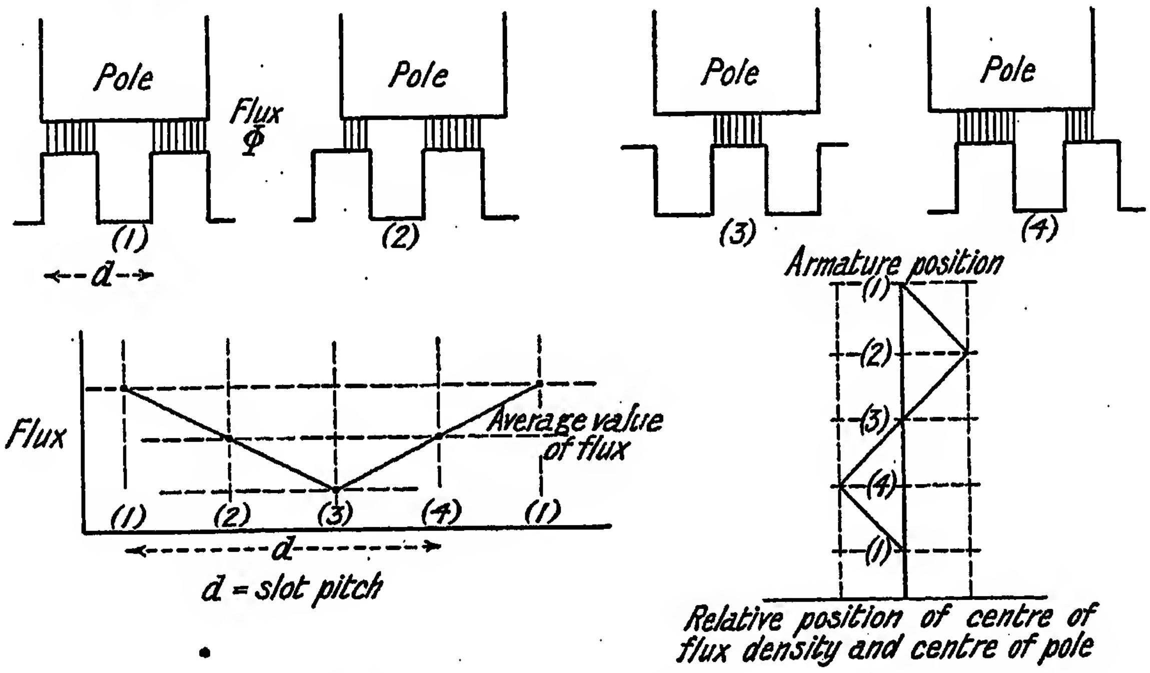


Fig. 4.—Flux variation in gap of generator.

form, for illustrative purposes, shows how the total flux will vary in the case of two teeth when passing through a distance equal to the pitch of a slot, i.e. the distance between the centres of two adjacent slots. It will be seen from this that the strength of the flux passing from pole to armature will vary in a periodic manner, depending upon the time taken by the armature in moving through one slot-pitch, as the armature will again be in position 1 after passing through another quarter of a slot-pitch beyond that shown in position 4. In other words, there is a periodic change in the total number of lines of force, and the point of maximum density moves backwards and forwards relative to the centre of the pole. The frequency of the change will, in effect, equal the number of teeth passing any given point in a second.

If N be the number of armature teeth per pole, S the number of poles, and R the number of revolutions per minute of the armature, then F, the frequency of the ripple $= N \times S \times R/60$. Now the fundamental frequency, P, of a machine is equal to $(R \times S)/(60 \times 2)$, and from this it is evident that $F = 2NP$, i.e. (the number of teeth per pair of poles) $\times$ (frequency of the current). As, however, the amplitude of the ripple is not constant, it cannot be truly represented as a single harmonic of the fundamental in that way.

The correct representation is the sum of two waves of frequency, viz. $P(2N + 1)$ and $P(2N - 1)$. In practice, the resulting ripple has a frequency $F = 2NP$, or $T \times R/60$, where T represents the total number of teeth on the armature.

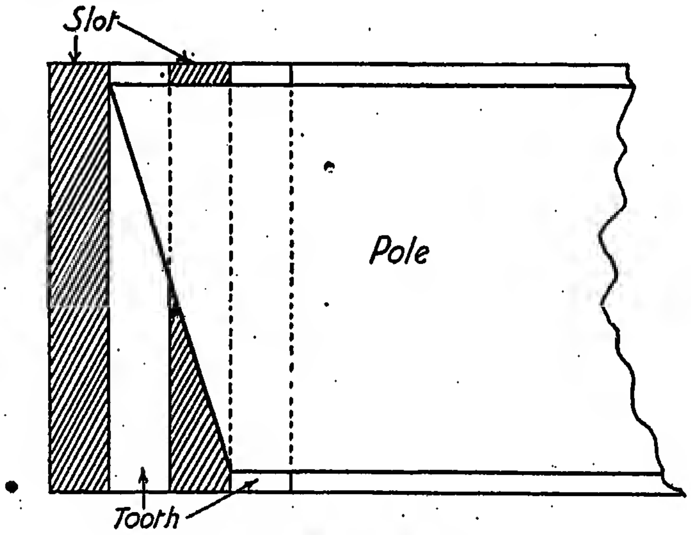
These slot ripples are usually of such frequency as to be specially objectionable to telephone circuits, as they fall within the speech frequencies. Table 1 shows the ripples at the frequencies in common use and with different numbers of slots per pole.

The reduction of these slot harmonics may be accomplished in several ways, but it is of course preferable to take them into account when a machine is designed, so that they may be restricted to a negligible quantity. The main consideration is to avoid variations in the magnetic field in the air-gaps, and conditions may be ...d by arranging for the gradual increase in the ...owards the tips of the pole. There will then ...responding gradual change in the flux in any particular tooth as it passes into or out of the influence of the pole. Further improvements may be introduced by skewing the pole-tips so that the teeth come gradually into or out of the influence of the pole. This is usually effected by cutting the pole-tips diagonally (see Fig. 5).

Harmonics are not so prominent if large air-gaps are used or if the slots are nearly closed. Harmonics are also reduced by making fractional the number of slots per phase per pole, i.e. by arranging that the number of slots per phase is not a multiple of the number of poles. With those conditions, the position of the slots and teeth under one pole will be reversed under another pole, and in that case the slot harmonic voltages in the conductors are out of phase under the two poles and tend to neutralize each other.

TABLE 1.

Slots per pole	Order of harmonic		Frequency							
			25 Cycles		40 Cycles		50 Cycles		60 Cycles	
6	11	13	275	325	440	520	550	650	660	780
9	17	19	425	475	680	760	850	950	1 020	1 140
12	23	25	575	625	920	1 000	1 150	1 250	1 380	1 500
15	29	31	725	775	1 160	1 240	1 450	1 550	1 470	1 860
18	35	37	875	925	1 400	1 480	1 750	1 850	2 100	2 220
21	41	43	1 025	1 075	1 640	1 720	2 050	2 150	2 460	2 580
24	47	49	1 175	1 225	1 880	1 960	2 350	2 450	2 820	2 940



Skewed Pole Tips

FIG. 5.

Harmonics due to flux.—In order to produce in the armature conductors an E.M.F. of sine wave-shape, it is necessary that the flux density should have a similar wave-shape, because as the conductors move at uniform speed the E.M.F. produced has the same wave-shape as the distribution of flux. It is possible to design machines with flux distribution at the poles approaching a sine wave-shape. This can be done in salient-pole machines by gradually increasing the air-gap from the centre to the tips. In non-salient-pole machines (in which the field is developed in an iron cylinder by

field windings placed in slots cut in the surface) it is possible so to distribute the field windings as to vary the strength of field to produce a flux corresponding approximately to a sine curve in shape. Fig. 6 illustrates the two types of pole and the shape of the flux distribution. In actual practice the method of distributing the conductors in the armature results in higher harmonics due to the flux density being neutralized to a great extent. If only one slot be taken for the armature conductor per phase, then the E.M.F. of the machine will have the characteristic of that conductor. The armature conductors per phase do not, however, occupy one slot only but are so arranged that the phase windings take up several adjacent slots. The result is that although the wave-shape of E.M.F. in each conductor is influenced in the same way by the distribution of the flux, the harmonics in the different conductors are not in phase and tend to neutralize one another. This is particularly the case with the higher harmonics.

"406. The deviation of wave-form from the sinusoidal is determined by superimposing upon the actual wave (as determined by oscillograph) the equivalent sine wave of equal length in such a manner as to give the least difference between ordinates, and then dividing the maximum difference between corresponding ordinates by the maximum value of the equivalent sine wave. A maximum deviation of the terminal voltage wave on open circuit from sinusoidal shape not exceeding 10 per cent is permissible except when otherwise specified."

The Sub-Committee on wave-shape standards of the Standards Committee of the American Institute have done a great deal of work in investigating the question. Both the British Committee and the American Committee had before them the evidence that harmonics between certain frequencies are particularly harmful

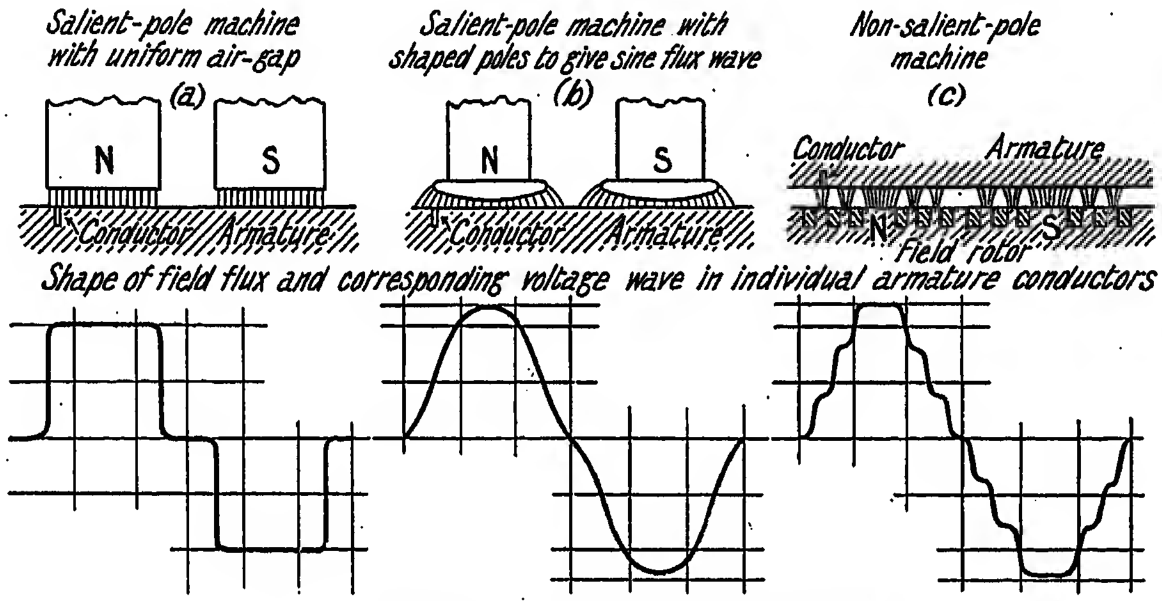


FIG. 6.—Flux distribution with different field poles.

The B.E.S.A. Standardization Committee on the wave-shape of alternators have considered that subject with reference, among other things, to the effects of irregularities in producing interference with telephone circuits. The present standard reads as follows, but the author understands that it is now being reconsidered and is in fact in the melting-pot :—

Wave-form of alternator.—The wave-form of an alternator on open circuit must approximate to a sine wave. In cases where wave-form is stated to be of importance at the time of ordering the machine, the maximum deviation of the actual wave from the equivalent sine wave when superimposed on it so as to give the least difference shall not exceed 10 per cent of the maximum ordinate of the sine wave; the equivalent sine wave being one having the same R.M.S. (root-mean-square) value and the same wave-length.

The Standardization Rules of the American Institute of Electrical Engineers on this matter read as follows :—

"405. The sine wave shall be considered as standard, except where deviation therefrom is inherent in the operation of the system of which the machine forms part.

so far as inductive interference is concerned. As a result of the American Committee's investigations, a telephone interference-factor meter has been devised which gives a direct reading showing how the wave-shape is loaded in this respect.*

The sensitiveness of the telephone receiver to the same current at different frequencies has been determined by observation. By multiplying each sensitiveness by frequency, a curve is obtained which shows the relative amount of sound interference caused by unit voltage of different frequencies in the power circuit. (It is of interest to note that Osborne states in his paper that "from the curve it is estimated that at 1 000 cycles the interference per volt is approximately 9 000 times that at 60 cycles, and 60 000 times that at 25 cycles.") The actual testing apparatus is based on the assumption that the interference effects of several harmonics can be obtained by taking the square root of the sum of the squares of the separate interfering effects. The testing circuit contains a filter network which gives readings according to the frequencies of the harmonics

* H. S. OSBORNE: *Transactions of the American Institute of Electrical Engineers*, 1919, vol. 38, p. 261.

present. It is stated in the same paper that approximate analyses of a number of cases show very clearly that, in general, the machines with high telephone interference factors are machines with large slot harmonics. It is believed to be the intention of both Committees to penalize wave-shapes which contain the frequencies mostly affecting telephones.

It should not be overlooked, however, that the third harmonic, although not in the range, is one very likely to cause disturbance to telegraphs. If a three-phase generator with earthed neutral point is feeding directly into a power line, i.e. one in which the voltage is not stepped up, it is nearly always the case that, as the conductors or load. Fig. 8 illustrates the conditions. If there is only the one earthed connection on the system the effect could be considered as a voltage effect only, except that a charging current alternates between the neutral point through the winding of the machine and through the capacity of the lines to earth. If the system is extensive this charging current may be very considerable, it being understood to be as much as 90 amperes in some cases in this country.

It should be pointed out that in addition to the third harmonic, odd multiples of the third may appear and act in the same way.

Two different methods of overcoming this trouble at

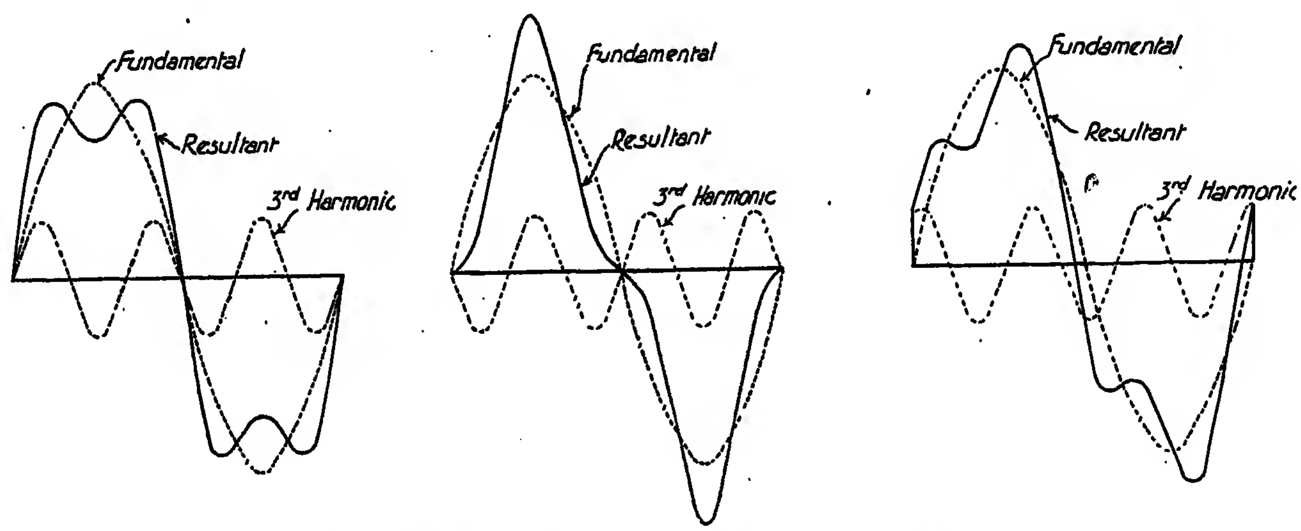


FIG. 7.—Resultant wave-shapes of fundamental and third harmonics.

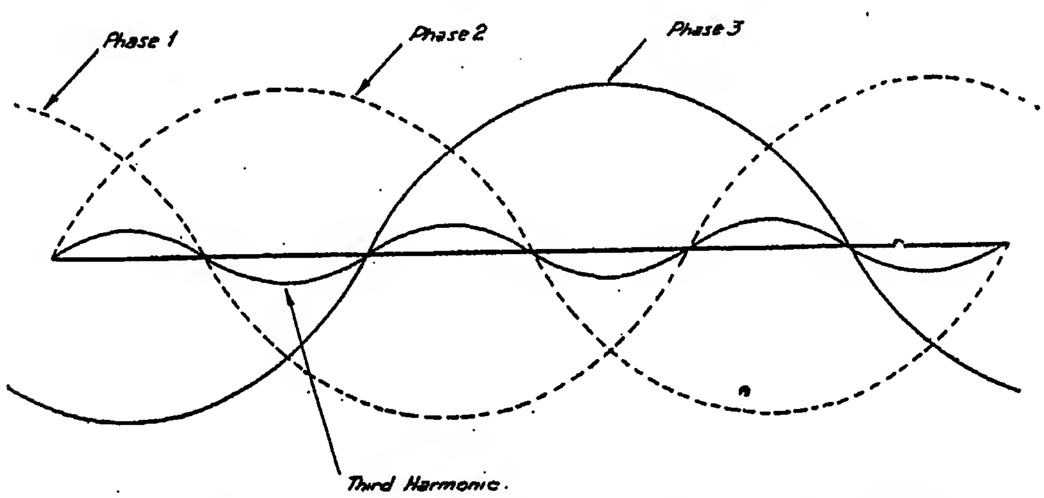


FIG. 8.—Fundamental waves and third harmonic in a three-phase system.

harmonics are in phase, a pronounced third harmonic shows itself as a heavy charging current oscillating between the earth connection and the three lines in parallel.

The effect of the third harmonic in distorting the wave-shape is dealt with in many textbooks and it may be considered superfluous to deal with it in detail here, but it has such an important bearing on interference from three-phase systems that the author would like to touch briefly upon it. Fig. 7 shows the three ways in which the fundamental and the third harmonic can combined, producing different resultant wave-shapes. each case, however, the third harmonic is in phase, s it completes one period in 120 degrees of the nental it does not appear between the three

the source have been suggested and, the author believes, have been successfully used on a small scale. The first was described by Prof. E. W. Marchant and T. H. Turney in a paper read before the British Association at Liverpool in September 1923. This method depends upon the placing of resonant shunts across the phases, the shunts being tuned to the harmonic that it is desired to suppress in the phase. Fig. 9 is taken from the paper.

The other method appears to have been applied by the British Thomson-Houston Co. to a machine causing trouble to telephone circuits and to lamps, and was described in correspondence in the *Electrician* and *Electrical Review* of the 2nd November, 1923, following on the published description of their device by Prof.

Marchant and Mr. Turney. This method is shown diagrammatically in Fig. 10 and depends for its effectiveness on the use of filters tuned to reject the frequency current which it is desired to suppress. This method has been employed in wireless reception for some years and is usually referred to as a "rejector" or "stopper" circuit.

In both cases the inductance and capacity are such as to produce resonance at the particular frequency,

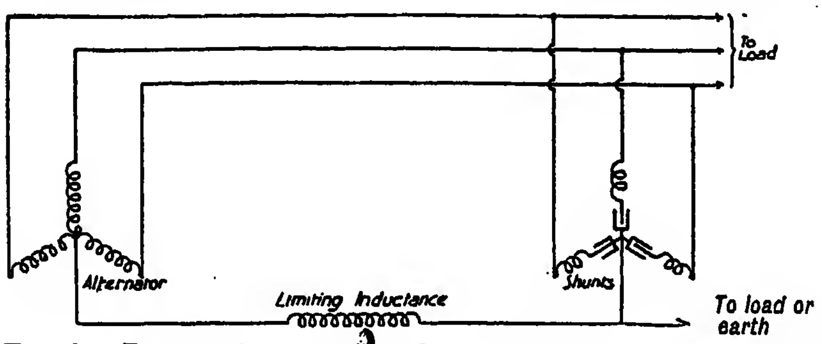


FIG. 9.—Resonant regulating shunts used with a three-phase machine.

but in the one application they are in series and so placed as to shunt the harmonic, whilst in the other they are in parallel and so placed as to prevent the circulation by producing a path of very high impedance to that frequency current.

Transformer harmonics.—With a transformer having an air core the flux and current have the same wave-

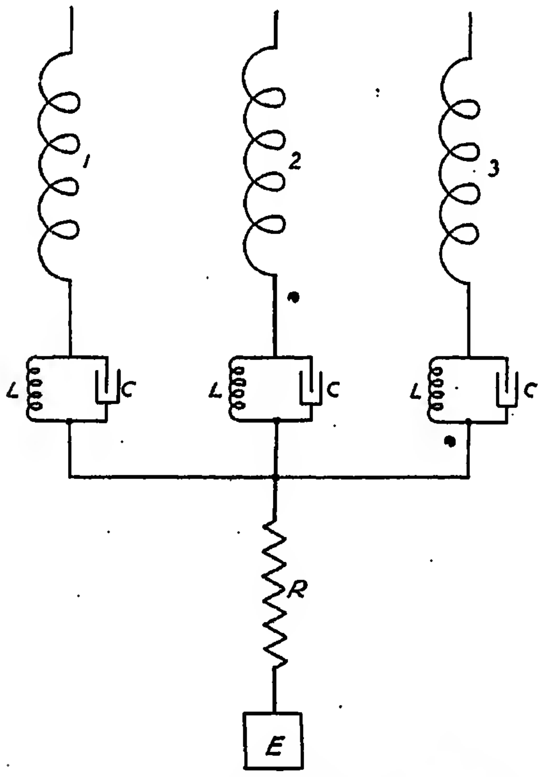


FIG. 10—Stopper circuit used with a three-phase machine.

shape, but that does not hold good where the core is of iron, which is usually the case in power systems. The relationship between flux and magnetizing current is $H \propto IL$, where H is the magnetizing flux, I the magnetizing current, and L the inductance. If L is constant for all values of current, the flux and the current will have the same wave-shape.

In the case of iron-core transformers, owing to the varying permeability, the inductance does not remain constant at all values of the magnetizing current, and the consequence is that the flux and the current cannot have the same wave-shape because the relation H/I must vary as direct changes. Further, if the usual hysteresis curve for iron is studied, it will be seen, that the flux is not proportionate to the current, there being a greater rate of increase at small current values than at large. Similarly, when current is decreasing, the

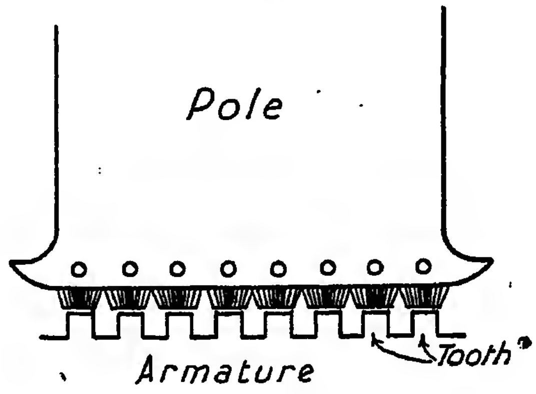


FIG. 11.—Density of field affected by damper bars.

flux is greater and changes at a slower rate than when the current is increasing.

The counter E.M.F. in a transformer has the same relative E.M.F. as the primary voltage at any instant of time, so that if the primary voltage is a sine wave, the counter E.M.F. and also the flux will be a sine wave; the current, however, will have some other shape and will contain harmonics. On the other hand, if the primary current is a sine wave the flux will not be a sine wave, and this will result in the counter E.M.F. not being a sine wave. In both cases the third and fifth harmonics are likely to be prominent.

As in the case of three-phase generators, the presence of the third-harmonic components or multiples thereof may be the cause of residual voltages and currents in

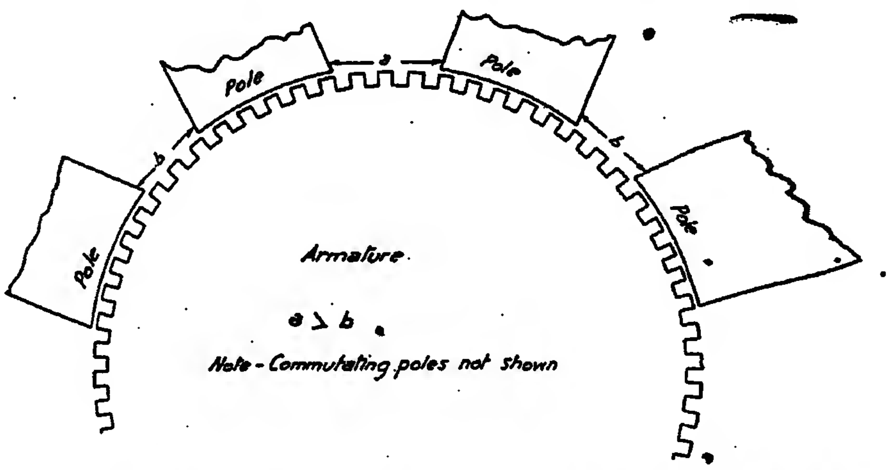


FIG 12.—Method of reducing ripples by shifting alternate poles half a slot-pitch.

the power line. The harmful effects can be modified and reduced by the type of connection used on the transformer and by limiting the exciting current. Star-connected banks with the neutral point earthed will result in voltage harmonics of three times the fundamental frequency and its odd multiples appearing between the lines and the neutral point, as the triple harmonics are in phase. If one side of the transformer is delta-connected, this provides a shunt path for the

triple-harmonic exciting current, and these harmonics reduce the residuals on the earthed star-connected side. The provision of a tertiary delta winding on a star-star connected bank of transformers will act in the same way. The general effects of the different combinations and connections are referred to later in the section dealing with electric light and power systems.

The magnetic density at which transformers are worked is a most important feature in the production of harmonics, as if the exciting current is large the effect is to develop large higher harmonics, i.e. to produce a flat wave. The reduction in the maximum magnetic density can be accomplished by lowering the impressed voltage per turn. Attention can perhaps be drawn here to the Californian Commission's General Order No. 52 on this point, which reads : "Transformer connections. In order that the wave shape of voltage and current may be distorted as little as possible by transformers, all connections on Class H power circuits shall have an exciting current as low as is consistent with good practice, which current shall not at rated voltage exceed 10 per cent of the full current. Except that for transformers without neutral ground connections on the line side, the exciting current at rated voltage need not be less than 0·2 ampere."

Class H power circuits are those having 5 000 volts or more between any two conductors, or 2 900 volts or more between any conductor and earth.

Core-type transformers are to be preferred to shell-type and single-phase units, as in the former the triple-harmonic exciting currents are to a certain extent suppressed by the mutual interaction of the cores, and the construction is such that the triple-frequency flux component has a very high resistance, the path being partly through the air or oil in the transformer.

The subject has formed the matter of many valuable papers, references to which are given in the bibliography, and the author is conscious that his description of the phenomena must accordingly appear sketchy.

Harmonics in direct-current systems.—As previously stated, harmonics are found in direct-current as well as in alternating-current systems. In the case of direct current, the ripples are usually slot harmonics and are produced in the same way as in alternating-current generators. There is, however, the difference that the slot harmonic in the case of direct current is not the combination of two harmonics. The amplitude of the harmonic is constant and its frequency is equal to the number of slots which pass a given point per second, e.g. in the case of an armature with 120 slots and running at 500 revolutions per minute the frequency of a slot harmonic will be 120 × 500/60 = 1 000.

Harmonics or ripples may be caused also by commutation, i.e. by changes in the current as the segments pass under the brush. The frequency of the ripple will be equal to the number of segments which pass a brush per second.

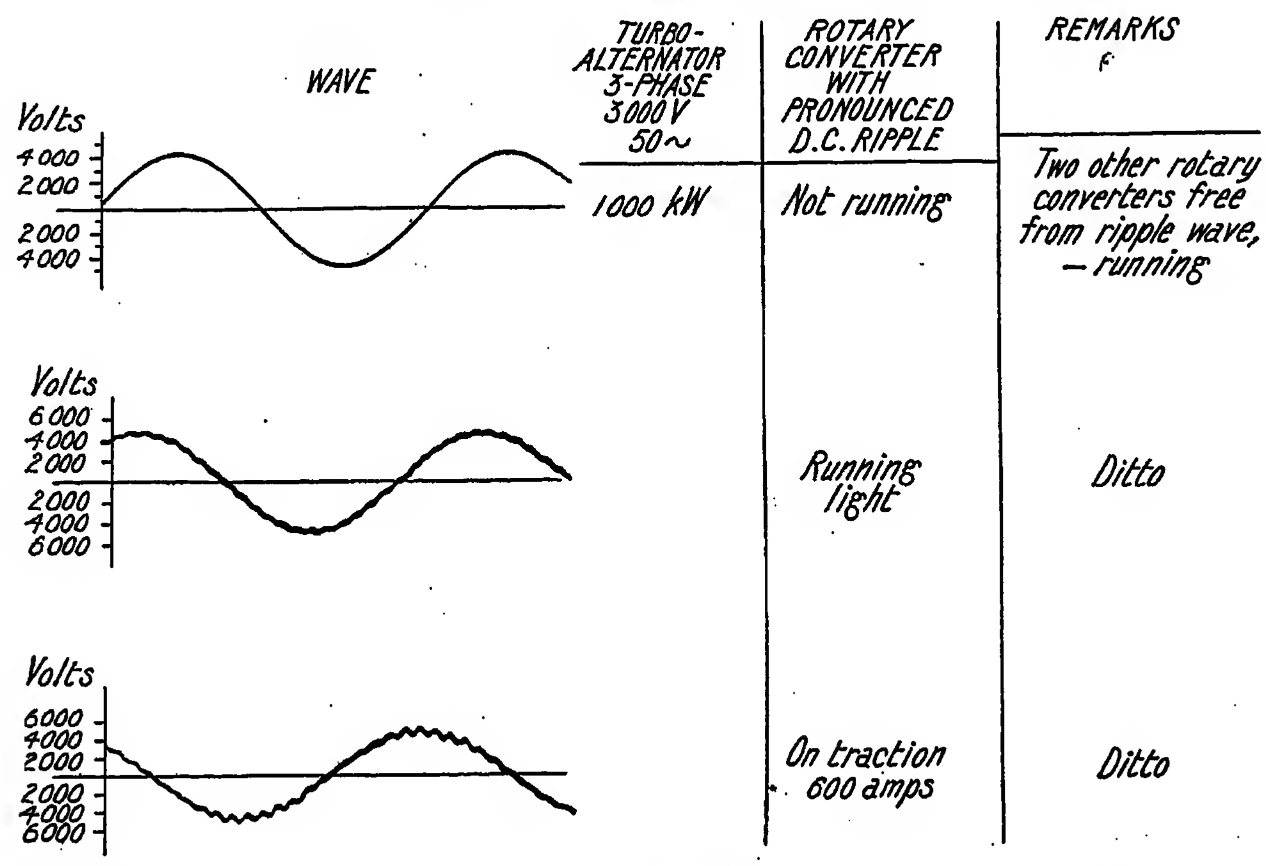


FIG. 13 (*a*).—Oscillograms showing reactive effect on a.c. wave (three-phase, high-tension) by rotary-converter d.c. ripples.

Rotary converters.—Of recent years a great deal of trouble has been caused by harmonics produced by rotary converters, as they are now commonly used for supplying direct current to traction systems where the power system is usually unbalanced and where the residual voltages and currents are considerable. As is well known, in this type of machine alternating current is collected by slip-rings on one side of the armature and taken to the commutator on the other side of the armature, where it is collected from the brushes as direct current. Slot harmonics are produced in the way already described, and in modern machines these have been found to be very disturbing to neighbouring telephone circuits. The speed of machines is usually such as to produce harmonic frequencies likely to

disturb speech. It has also been found that the slot harmonics may be greatly accentuated by the arrangement of the damper bars in the pole-shoes. The number of these bars varies in different makes of machine, and in certain types where severe interference has occurred the distance between the damper bars has been found to be equal to the pitch of the slots (see Fig. 11). It is thought that the damper bars cause changes in the density of the flux or tufting of the field in their neighbourhood, and, as the pitch or distance between

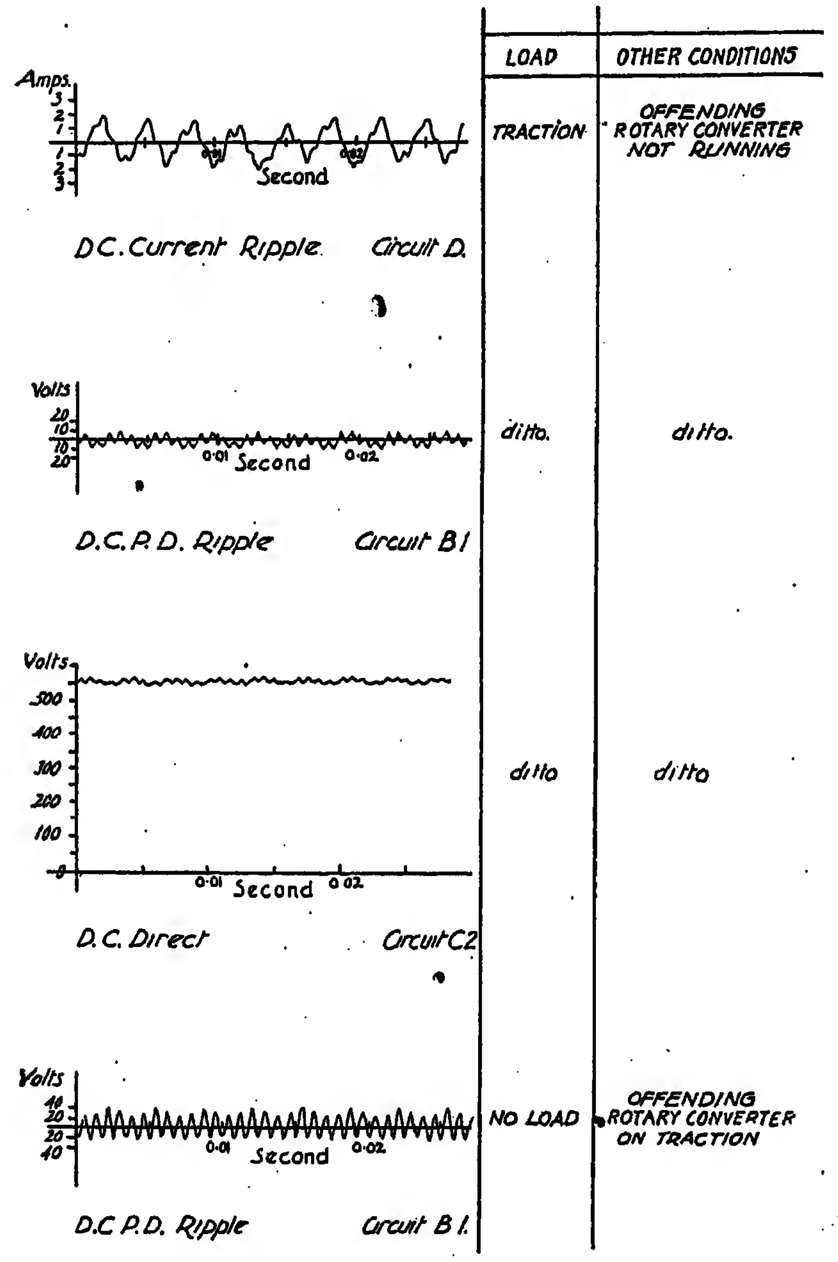


Fig. 13 (*b*).—Oscillograms showing d.c. ripples on other rotary converters in same station.

the slots is equal to the distance between the tufts, there is simultaneous cutting of the denser parts of the field by all the conductors of the armature and the amplitude of the harmonic is consequently increased. One of the remedies is to shift alternate pole-shoes or poles half a slot-pitch, or each pole-shoe or pole a quarter of a slot-pitch, one in one direction and the next in the opposite direction. In either case there will then be alternate short and long gaps between adjacent pole-shoes, and, as the conductors will not be affected simultaneously by the tufts, the harmonics will be out of phase and the ripple will be largely wiped out (see Fig. 12).

It may be of interest to show here the improvements effected by alterations to machines which had been found to offend in this respect, in this case by altering the spacing between pole-shoes. The interference was caused by a tramway system, the direct current for which was obtained from rotary converters run from a three-phase 3 000-volt 50-period supply. There were three rotary converters, two by the same maker and of 600 kW and 300 kW respectively, and the third, by another maker, of 1 000 kW. The disturbance was found to be due to the latter machine only. Oscillograph records were taken and it was seen that there were ripples superposed upon the direct current. These ripples were of two frequencies, 1 200 and 300 per second, and of 30 and 40 volts R.M.S.; the 1 200-frequency ripple caused serious interference with the telephone service. Among other things the oscillograms showed that the main a.c. wave was free from objectionable ripples except when the 1 000 kW rotary converter was in use, indicating that the ripple originated with the converter and reacted on the a.c. side. Figs. 13 (*a*), (*b*), (*c*) and (*d*) are copies of selected oscillograms taken before the machine was altered, followed by similar ones taken after the alterations to the machine. The alterations had the effect of reducing the value of the ripples to about 5 volts R.M.S., the frequency being increased to over 2 000 per second and the result being that the interference was rendered inappreciable.

Similar improvements have been effected in other towns and it should be observed that this trouble has not been confined to one make of machine. In one instance where the trouble was thought to be uninfluenced by the spacing of the damper bars it was found that to shift alternate pole-shoes was more effective than to skew the pole-tips.

The oscillograms reproduced in Fig. 14 are of interest as showing the results when machines of the same type are worked in parallel, some having been altered and the others unaltered. In the figure, converters 1 and 4 have been altered by shifting the poles, 2 and 3 being as originally designed. It will be seen that the unaltered machines dominate the effects and that there is a marked change when the altered machines are run singly and in parallel.

M. B. Field in a paper on "The Study of Phenomena of Resonance in Electric Circuits by the aid of Oscillograms," read before the Institution in 1903,* showed that in the cases he was investigating the ripples originated in the generator, i.e. the high-pressure a.c. side, and not in the rotary converter. This does not appear to be the case in most instances, but it was definitely proved in one investigation by the Post Office that the sixth harmonic, which was present with the converter working normally, disappeared when the machine was driven from the starting motor. This is shown in the oscillograms in Fig. 15.

The subject of harmonics or ripples in rotary converters is very fully dealt with in F. P. Whittaker's paper on "Rotary Converters, with special reference to Railway Electrification," read before the Institution in 1922.† The paper is particularly interesting as

* *Journal I.E.E.*, 1903, vol. 32, p. 347.
† *Ibid.*, 1922, vol. 60, p. 501.

showing that in certain cases the sixth harmonic may originate in the supply side of the system.

It appears that this may be due to the presence of the fifth and seventh harmonics in the a.c. supply for the following reason: If the converter is worked with six phases, then the third harmonic on the supply side will have no effect; but if there is a fifth harmonic to the d.c. brushes, and therefore it induces at the d.c. brushes an E.M.F. of sixth frequency.

The seventh harmonic, however, rotates in the same direction as the fundamental and also therefore produces a sixth harmonic at the brushes. Similarly the 11th and 13th harmonics produce the 12th harmonic.

Mercury-arc rectifiers.—The mercury-arc rectifier

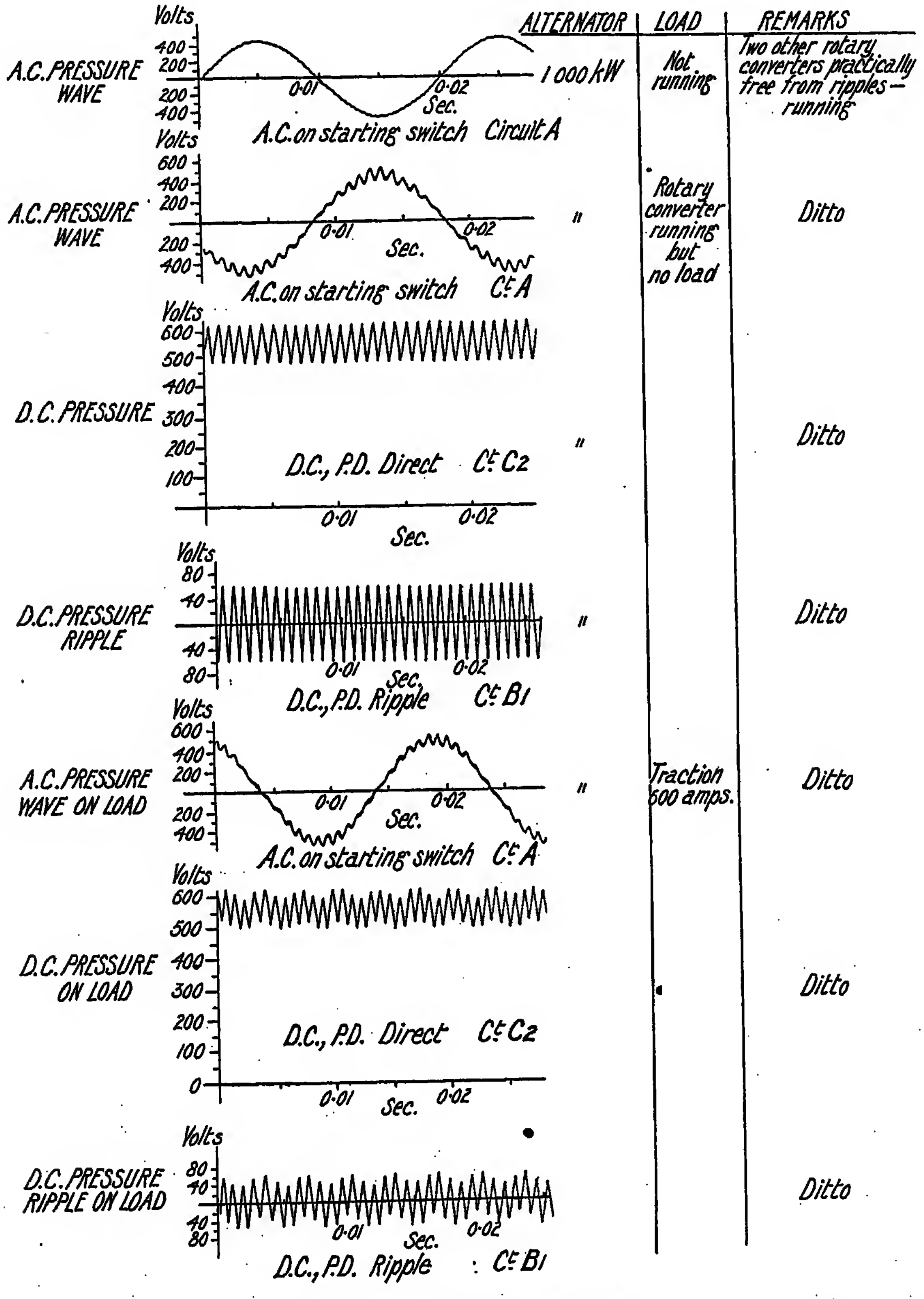


FIG. 13 (*c*).—Oscillograms showing rotary-converter d.c. ripples and reactive effects on a.c. wave at slip-rings of converter.

present this will flow, as the transformer and converter form a closed circuit. These currents will then form a rotating field of five times the normal synchronous speed relative to the armature, the rotation, however, being in an opposite direction. Since the rotating field of the fifth frequency rotates with five times the normal synchronous speed relatively to the armature, it must rotate with six times the synchronous speed relatively appears to have entered the field as a serious rival to the rotary converter for the conversion of alternating into direct current. There is therefore a piquant interest in any information which will compare the two in the matter of inductive effects. The author does not know any cases where the rectifier is being used for traction work which would be a severe test in this respect, but there are many places where it is

used for lighting, etc. One would expect rectifiers of this character to produce harmonics, and this has proved to be the case. Telephone interference has been caused and the author is fortunate in having had placed at his disposal an account of the successful methods adopted to overcome the trouble. Prof. E. W. Marchant was called in to advise on the case in question, and his description of the steps taken is given in an appendix.

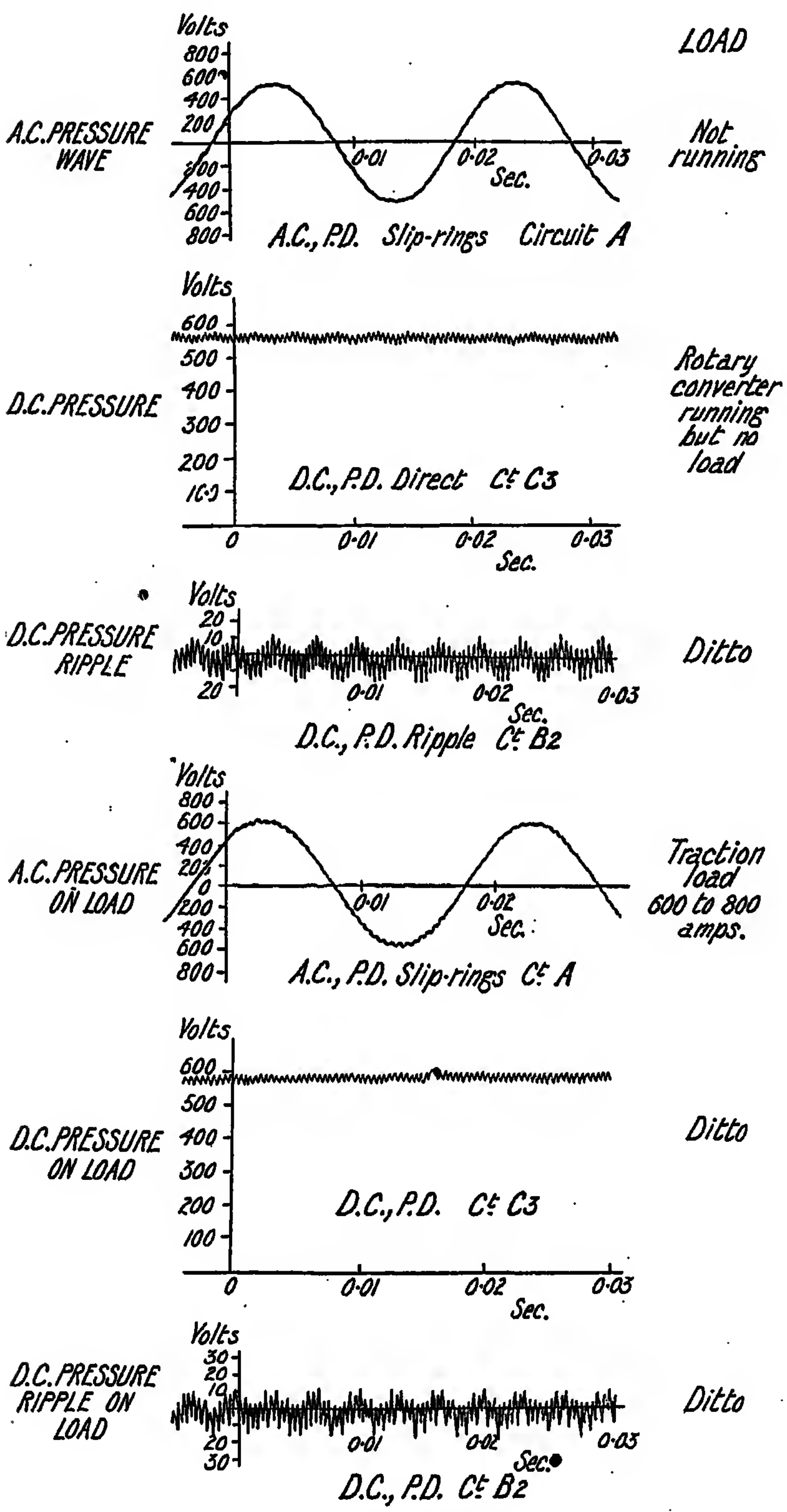


Fig. 13 (*d*).—Oscillograms showing effect of altered rotary converter.

Transpositions.

The voltages produced in a telephone circuit by the electric and magnetic fields may be separated into two effects, usually referred to as transverse and longitudinal induction. The transverse induction is that produced between the two sides of the circuit, whilst the longitudinal induction is that produced between the two sides of the circuit and earth, or along the circuit. The induced voltages due to the former effect will cause currents to circulate through the terminal apparatus, whilst the latter may result in currents through the apparatus if there is a difference in the impedances and capacities to earth of the two sides of the circuit.

The author may perhaps be pardoned for indicating in its simplest form the effects of the electric and magnetic fields on a neighbouring telephone circuit, and the benefits to be obtained by transposing the latter. The simultaneous occurrence of electric and magnetic induction is the normal result of the proximity of power lines and communication circuits. Fig. 16 shows a non-transposed telephone circuit and a disturbing power line. The effect of one wire only of a power circuit is considered. The (*a*) wire of the telephone circuit, being nearer than the (*b*) wire, has a higher induced potential due to the electric field and at the same time a larger E.M.F. from the magnetic field. Assuming that the potential of the wire of the disturbing circuit is increasing in the positive sense as shown, and the current increasing in the direction shown by the arrows, then the illustration indicates what is occurring at that time. The telephone receiver at B will be more disturbed than that at A.

If now a transposition is made in the telephone circuit at the right point the magnetic effect at the terminals can be eliminated, as shown in the figure. On the other hand, however, the electric field effects are not so completely neutralized. There are four points at which a current divides and flows in opposite directions, i.e. 1, 2, 3 and 4. Single transpositions are of course not effective with long exposures, and theoretically the result of electric induction could be eliminated only by an infinite number of transpositions.

It should be observed, too, that the actual induced voltage on the wires due to the electric field, i.e. the longitudinal voltage, is not reduced by the transpositions, although the effect of that voltage on the apparatus may be neutralized with the lines in good condition. Further, it is extremely difficult, and sometimes impossible, to secure such an accurate electrical balance to earth of the two sides of a complete telephone circuit as to reduce the disturbance of its electrical field to a sufficiently low figure for satisfactory working. The use of the earth for signalling purposes is an essential feature of modern telephone practice, and although relays and retardation coils are tested for balance, which ensures that they will be unaffected by neighbouring telegraph and telephone circuits, this may not be the case in the very much stronger fields produced by power circuits. To enable this part of the problem to be visualized, Fig. 17 has been prepared, which shows in skeleton form the principal types of standard circuit with speaking conditions. For the sake of simplification, the subsidiary apparatus for signalling and clearing has been omitted from the diagram.

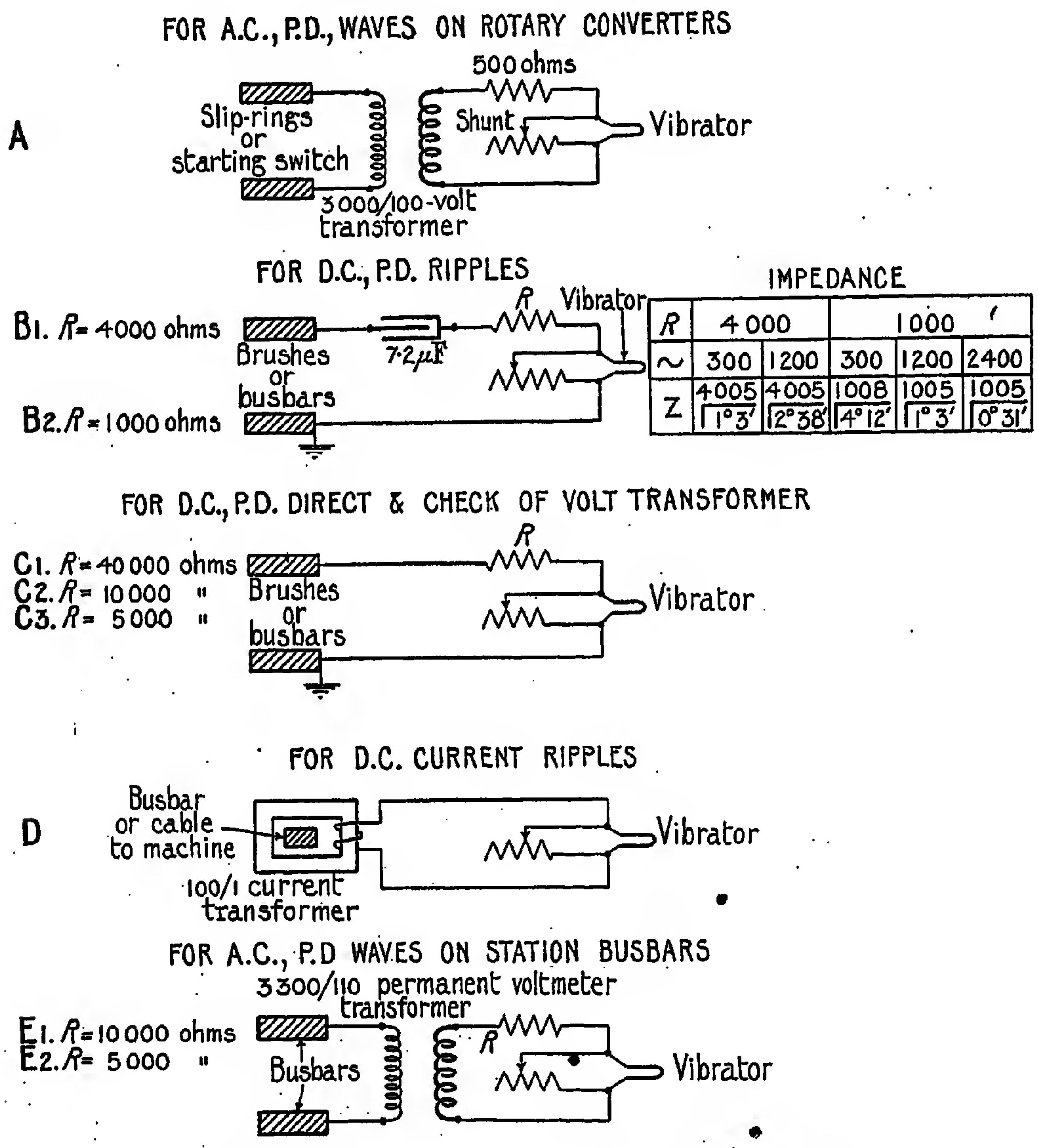
The transposition in the positions of wires forming the circuits of telephone and power circuits, where these

circuits run parallel, is a most important method for reducing inductive interference. The object of transpositions in a communication circuit is to equalize the electrical effect of near-by influences so that the wires are similarly affected in a given length. The transposition of power wires will produce neutralizing effects in the telephone circuits due to balanced voltages and currents, whilst to transpose the telephone wires tends and a very good balance of the telephone circuit is required for satisfactory working.

Two methods of transposition are employed in this country. The older system is known as the "twist," in which four wires (two circuits) are taken as a unit and occupy at the insulators the four corners of a square, the diagonals comprising a circuit. At successive poles each wire changes its position to the next

Note:-

	1st Test R 1550	2nd Test R 1564
Resistance of vibrator	< 3 ohms	about 8 ohms
" " " shunt	0 to 13 ohms	0 to 35 ohms



R	4 000		1 000		
~	300	1200	300	1200	2400
Z	4005 ∠1°3′	4005 ∠12°38′	1008 ∠4°12′	1005 ∠1°3′	1005 ∠0°31′

FIG. 13 (e).—Circuit connections for oscillograph records.

to equalize the inductive effects in the two sides of the circuit, whatever may be the cause of such effects.

It has been the practice of the Post Office for many years to transpose telephone wires in order to prevent disturbance from telegraph circuits and cross-talk between the telephone circuits themselves. The inductive effects produced by a single-wire telegraph circuit on a telephone circuit carried on the same pole line may be considerable, as the length of parallelism may be great and the separating distance as low as 12 inches, corner of the square and thus in four spans completes a spiral, the twist being right-handed (Fig. 18). The other system is that employed in America for many years by the American Telegraph and Telephone Company, in which the wires are run straight for a certain number of spans and their position is changed at definite points. The wires comprising the circuit in this system are erected on the same arm, and the transposition points vary according to the position of the arm and of the wires on the arm. There are several

variations of the system and it would occupy too much space to go into them in detail here, as they are all more or less complicated. Both the "twist" system

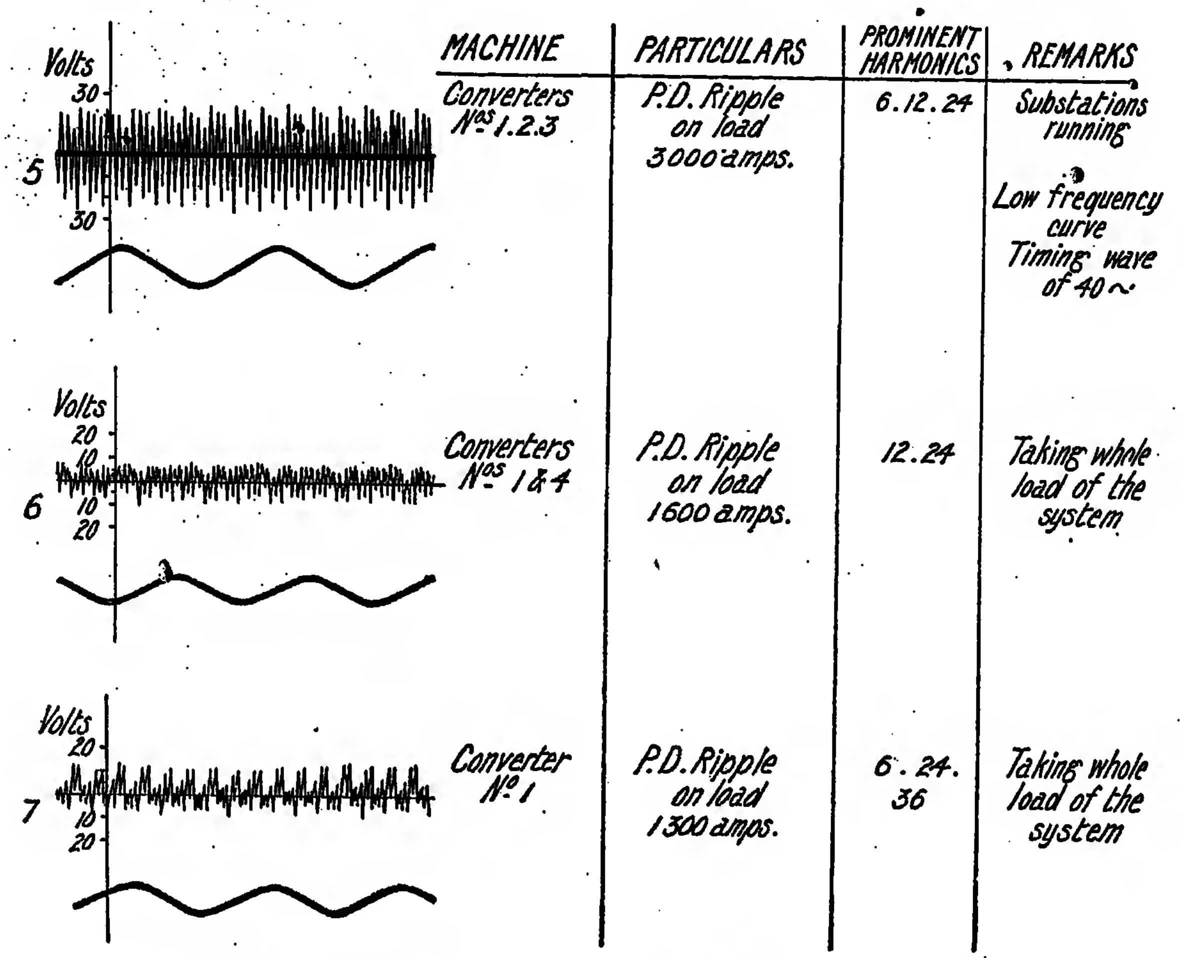


FIG. 14.—Characteristics of rotary converters running in parallel.

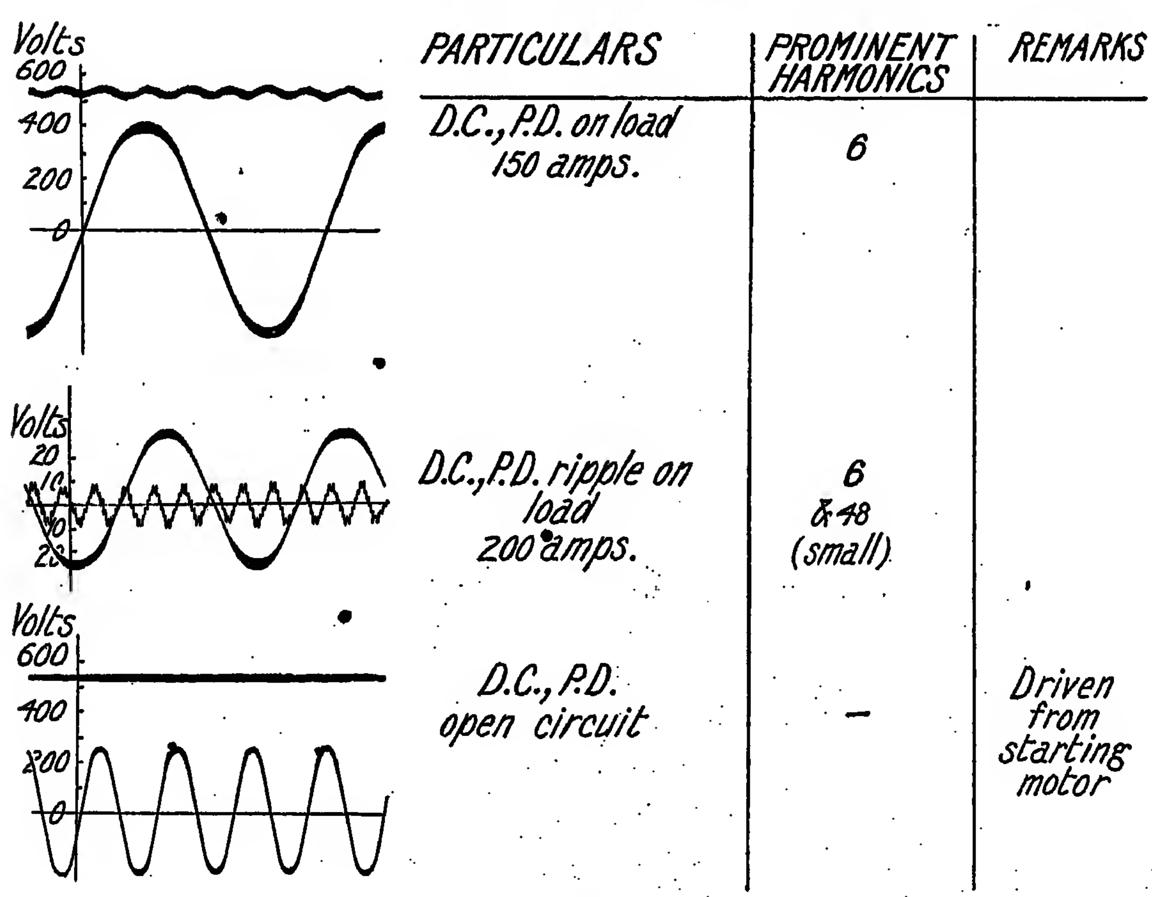


FIG. 15.—Oscillograms showing sixth harmonic originating on a.c. side.

and the latter transposition system are equally efficacious in preventing inductive effects and cross-talk from neighbouring telegraph and telephone circuits. The American system adopted by the Post Office is based on a unit length of 8 miles. Fig. 19 shows the type of transmission scheme and is self-explanatory.

As pointed out previously, the transposition of power wires will not reduce the effects of residual voltages and currents except in so far as it effects an improve-

ment by balancing the capacities to earth of the several conductors. The transposition of power conductors will, however, reduce the effects of balanced voltages and currents by producing mutually neutralizing effects in neighbouring communication wires. Power wires on traction systems cannot, of course, be transposed. In the usual case it is a three-phase three-wire extra-high-pressure line, as there is little single-phase overhead

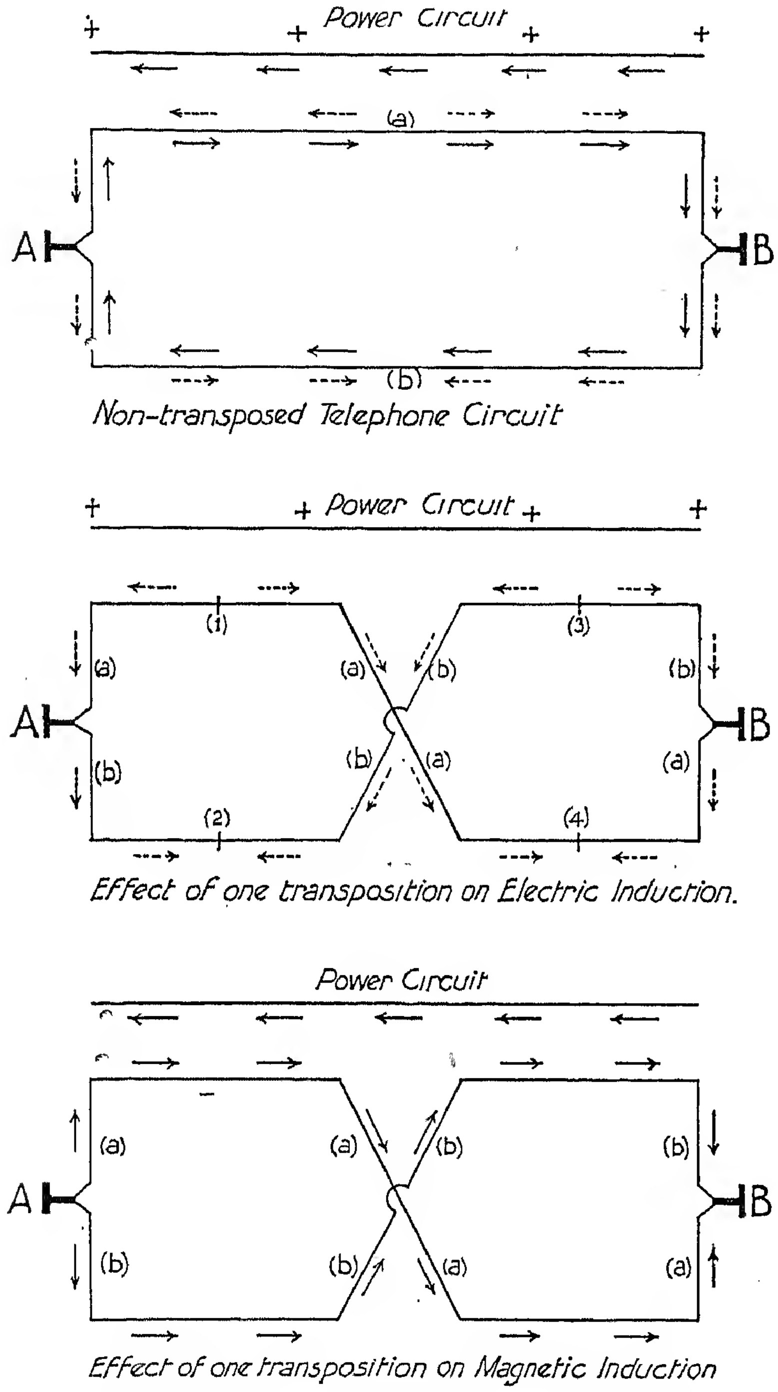


FIG. 16.—Effect of transposition on induction.

--> indicates current due to electric induction.
—> indicates current due to magnetic induction.

work. The section of the power circuit in which each conductor occupies each of the conductor positions for equal distances is usually defined as a "barrel." Fig. 20 shows a co-ordinated scheme where a three-phase and a single-phase line run parallel with a telephone line.

The Californian Commission's report limits the maximum length of barrel in the case of a single-circuit three-phase line to 12 miles for circuits of triangular configuration, and to 6 miles for other forms. Single-phase and two-phase circuits have to be transposed at intervals not exceeding 4 miles.

PARALLELISM.

It is obvious that one of the most important factors in preventing and minimizing inductive interference is to avoid conditions where power lines and communication circuits will run parallel to each other. It should be an axiom that where parallelism cannot be avoided the greatest possible separating distance should be provided. This is important not only in connection with inductive effects resulting from the normal working of the power line, which may be small if proper precautions are taken, but because it is impossible to guarantee that some abnormal occurrence on the power system may not by its unbalancing effects cause serious disturbance. One naturally asks what are the permissible conditions, and one seeks for a simple rule which will apportion due weight to the factors and give a safe answer. Unfortunately, these factors are very complicated, involving, as they do, not only such simple matters as separating distance, lengths of exposure, normal voltages and currents and frequencies, but also wave-shapes of transformers and generators, capacities and inductances of power and communication circuits, and the configuration and separation of the power and communication wires.

The Californian Joint Committee did not commit themselves beyond stating that "every reasonable effort shall be made to avoid parallels and where there are parallels they should be as short as practicable." Further, "the power lines and communication lines shall be kept as far apart as practicable and this separation should be at least equal to the height above ground of the power wires, except when closer proximity is unavoidable."

There are three considerations to be borne in mind. These are the induced effects which may be produced by (*a*) balanced voltages and currents, (*b*) the residual voltages and currents, and (*c*) abnormal occurrences arising out of faults, switching, etc. The first-mentioned may, perhaps, be forecast and allowed for; (*b*) is a more difficult matter, and (*c*) more difficult still, the factors being modified by all types of fault and by the position of the communication line in respect to the generating station and the position of the fault. The inductive effects of balanced voltages and currents are the most tangible to handle, and in the case of a three-phase overhead line the theoretical effects have been considered by several investigators. To forecast the results of those effects and those of the residual voltages and currents on neighbouring telephone and telegraph circuits in terms of noise value and mutilating effects on telegraph signals is, in the opinion of the author, to enter into the region of prophecy and he is not in a position to commit himself on the matter. As regards actual maximum tolerable values, those taken in the Californian report are no doubt near the mark in the case of telephones; that is, the extraneously induced current in the receiver should not exceed in its noise-producing value the effect of 10 micro-amperes at a frequency of 240 periods per second; but those taken in the case of telegraphs, viz. the extraneously induced current at the circuit terminals, should not exceed 2 milliamperes at a frequency of 60 periods per second, or its equivalent at any other frequency, e.g. 1 mA at

25 periods per second appears to be on the high side. The types of telegraph apparatus and their sensitivities vary considerably and the author would place the maximum figure at 0·5 milliampere for this country.

The method of calculating the electric and magnetic effects would form the subject of a separate paper, and the author would refer those sufficiently interested to the treatment by L. P. Ferris, in the Californian Report, and by E. Parry in the *New Zealand Journal of Science and Technology*, 1919, vol. 2. Parry's theoretical calculations of the electric effects were concerned with the Lake Coleridge–Christchurch 66 000-volt three-phase transmission line. Figs. 21 and 22 are reproduced from the paper and refer respectively to the calculations of the electrostatic and electromagnetic fields upon a neighbouring telephone circuit. Fig. 21 shows the maximum value to earth of the electrostatically induced E.M.F. in the telephone wire 18 ft. above the ground at varying separating distances from the power line which has an equilateral triangular formation with 6 ft. spacing and the bottom wires 32 ft. 2 in. above the ground. In the case of wires actually erected on the power-line poles 6 ft. 5 in. below the bottom arms, Parry's calculation gave a maximum pressure to earth of 4 940 volts, and he remarks: "Hence the necessity of ample drainage coils and transformers insulated for high voltage, insulated platforms and other devices for the security of the employees."

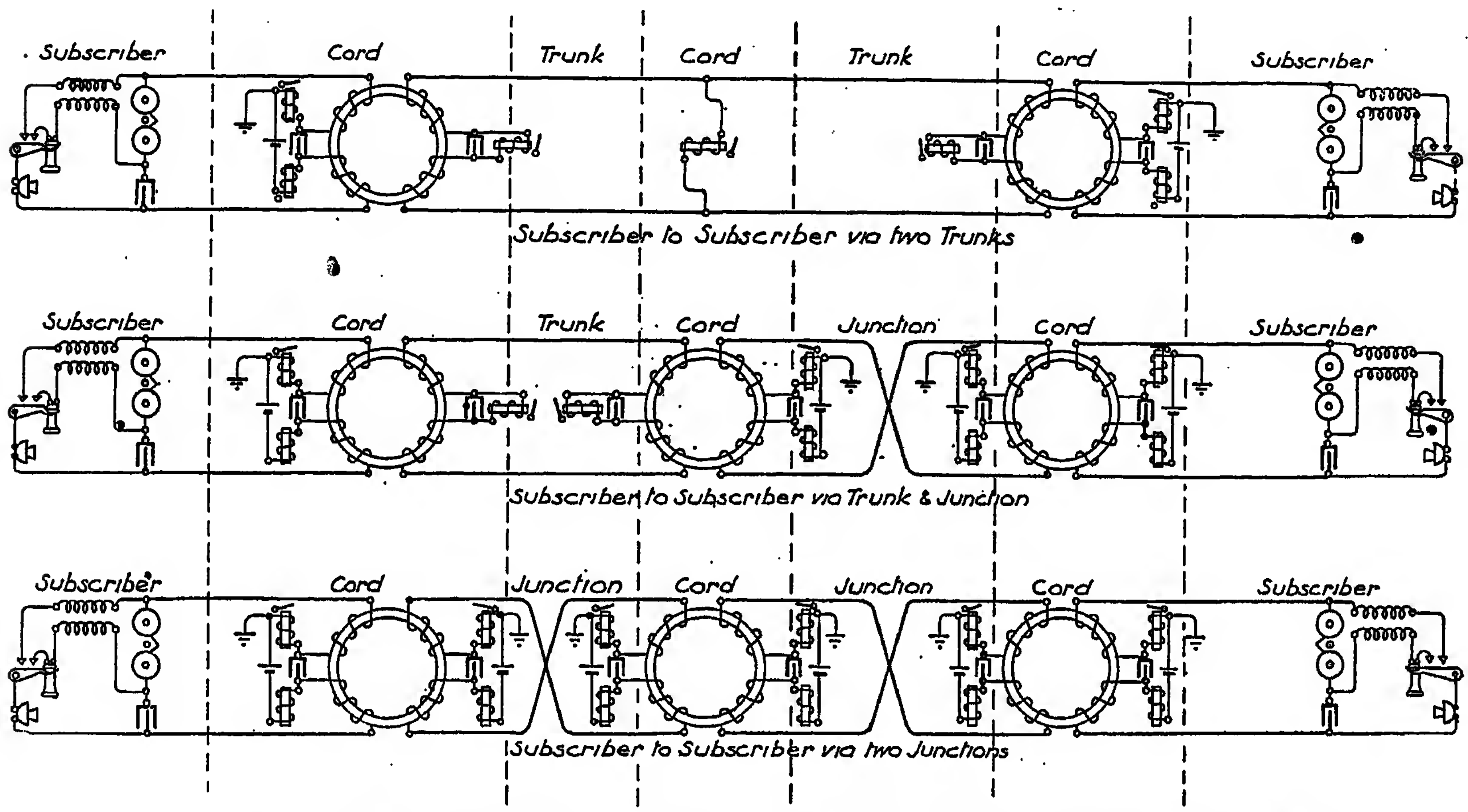


FIG. 17.—Typical long-distance telephone connections. Skeleton diagram showing all earth connections.

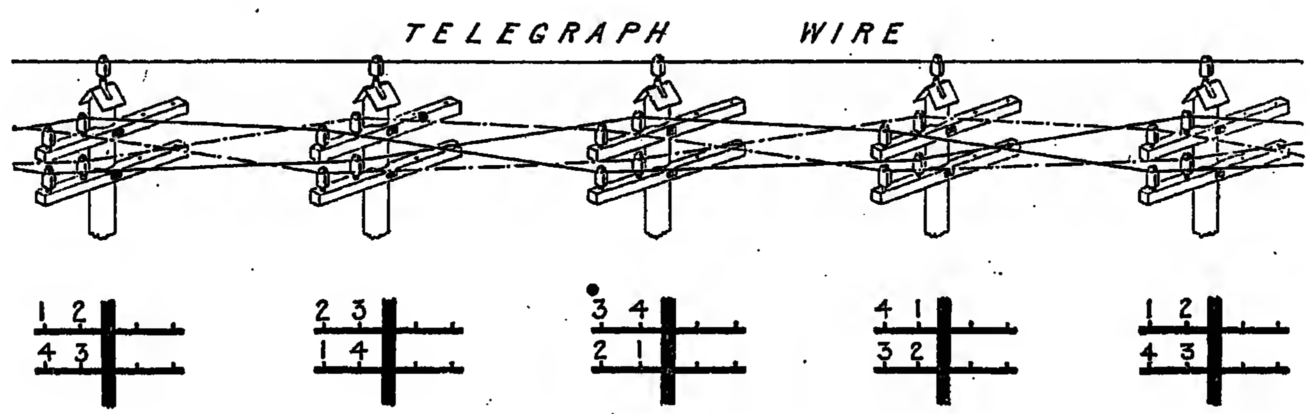


FIG. 18.—Twist system of transposition.

Fig. 22 shows the maximum voltage per mile induced in a telephone circuit with 100 amperes in the power line. The calculated induced voltage per mile of wire in the case of the telephone wires on the power-circuit poles was 5·03 volts per mile, and this applied equally to each leg of the circuit. Owing to the difference in phase of the effects, however, there would be a difference of 2·1 volts between the two sides at any instant of time.

Parry's calculations of the effects of the electric field were verified by actual measurements made by Caldwell and Marsden (See the same *Journal*, January 1921). Observations made on a line situated 26 ft. from a 66 000-volt power-transmission line showed voltages between 100 and 1 140 on various wires under varying conditions caused by earthing neighbouring conductors. Insulated telephone wires erected on the poles carrying the power wires had pressures to earth of between 150 volts and 1 850 volts according to the different conditions as regards earthing of adjacent wires. Using Parry's formula the authors state that for a long telegraph wire of No. 11 S.W.G. (200 lb. copper) 18 ft. above the ground the induced voltages for different separating distances will be as shown in Table 2.

The quantity of electricity Q induced on the wires should they be earthed is roughly proportional to the voltage indicated above, so that the energy of discharge, which is proportional to QV, will fall off with the distance at a rate proportional to the squares of the above figures. It should also be pointed out that the induced voltage will be less if the wires concerned extend beyond the influence of the power line, as the effective capacity per unit length will be increased accordingly.

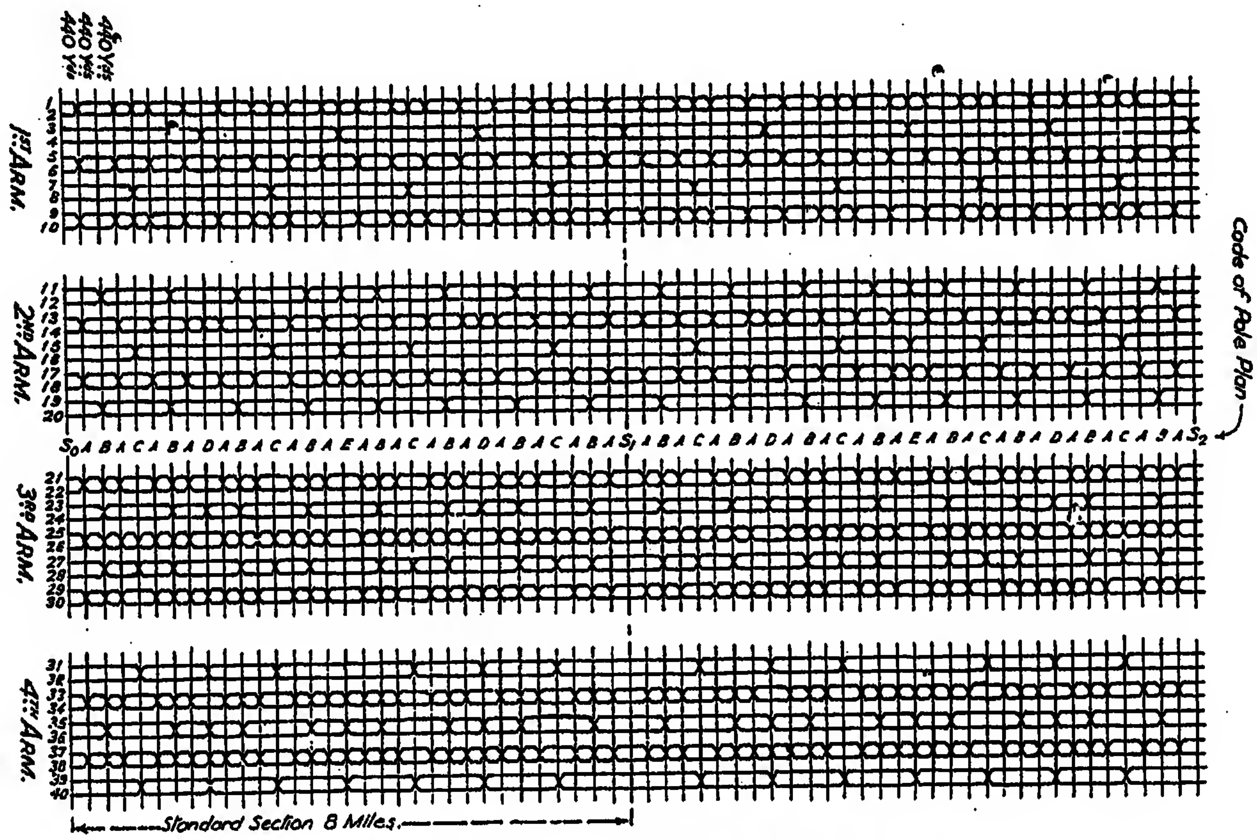


FIG. 19.—American system.

The 5th, 6th, 7th and 8th arms will be transposed like the 1st, 2nd, 3rd and 4th arms respectively, with the exception that at the 1st, 3rd, 5th, etc. S poles, all pairs except 43–44 will be transposed.
For a saddle pair cross as shown for 35–36. For two-wire arms or pole brackets cross as shown for 5–6, 15–16, etc.
For four-wire arms cross as shown for 3–4, 7–8, 13–14, 17–18, etc. For six-wire arms cross as shown on plan, omitting 1–2, 9–10, 11–12, 19–20, etc. For eight-wire arms cross as shown on plan, omitting 5–6, 15–16, etc.

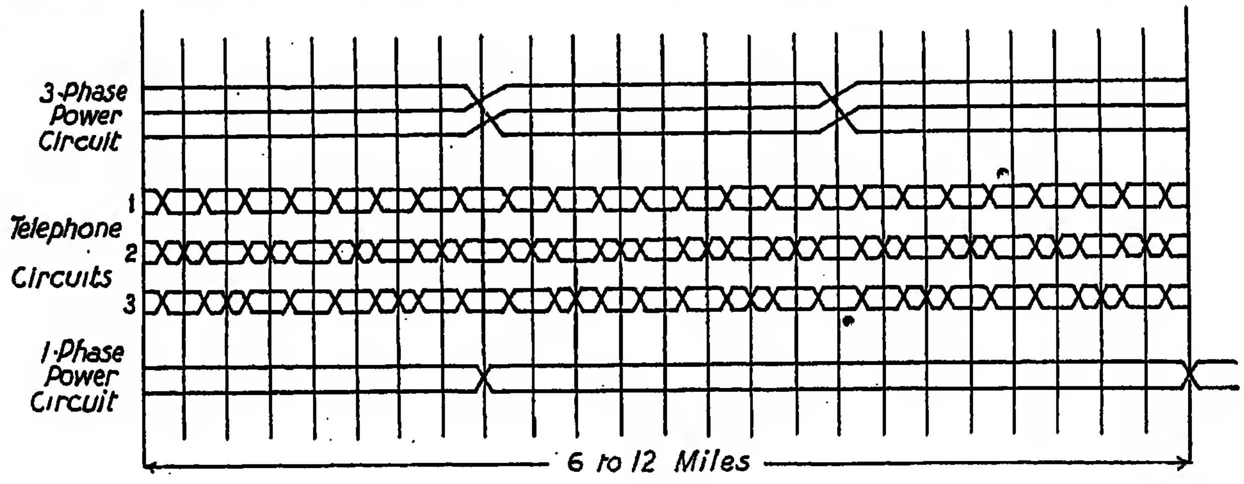


FIG. 20.

TABLE 2.

Transmission line voltage	Induced voltages (R.M.S.)		
	1 Chain	2 Chains	3 Chains
100 000	200	52	21
66 000	131	34	14
11 000	22	6	2

Although the Californian Joint Committee did not commit themselves to definite proposals as to what constitutes a dangerous parallel, they included in their report proposals for arriving at a basis. The Committee did not agree as to the acceptability of these proposals should be transposed to reduce balanced voltages and currents, and other charts which deal with residual voltages and currents and indicate the conditions from which interference with telegraphs and telephones can be anticipated.

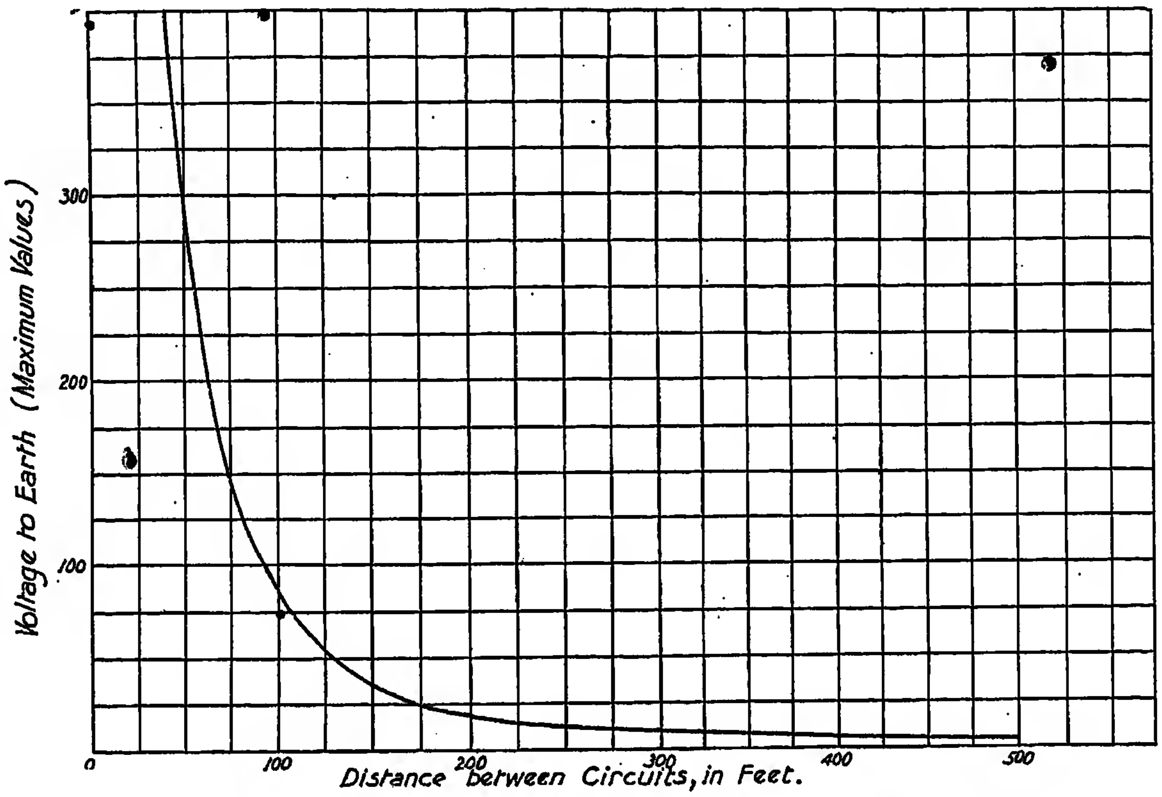


FIG. 21.—Electrostatic induction between power and telephone circuits.

Power circuit: 7/0·135, 66 000 volts, 50 periods, three-phase.
Telephone circuit: No. 11 S.W.G.

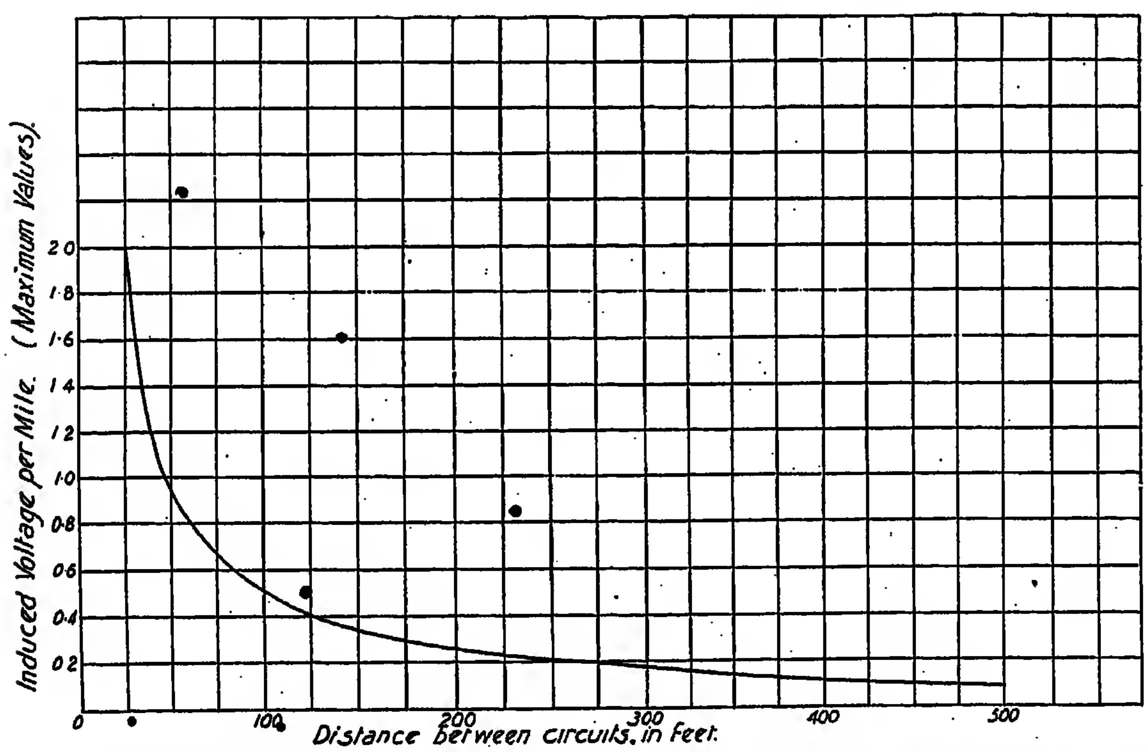


FIG. 22.—Electromagnetic induction between power and telephone circuits (per 100 amperes, max. value).

Power circuit: 7/0·135, 66 000 volts, 50 periods, three-phase.
Telephone circuit: No. 11 S.W.G.

but put them forward solely as a preliminary study and a guide to those undertaking further studies of this nature. In their report are a number of charts which are the suggested basis of conditions that should be a guide for deciding whether power circuit wires

In the case of balanced voltages and currents the charts are based on the assumption that balanced voltages will interfere with telephone circuits if the product of the length of parallel running in miles and the induced pressures between conductors and earth

in volts exceeds 200 volt-miles, and that from balanced currents will interfere if the average induced voltage along conductors exceeds 0·5 volt at 60 cycles per sec. For telegraph circuits the figures are respectively 300 volt-miles and 1 volt at 60 cycles. An indication of what this means can be gathered from the exemption from transposition given to lines on private rights of way in the Californian final report, subject to the conditions in Table 3 and to the power line not paralleling the highway or communication line with a closer proximity than that given by 1 mile in 30 miles of parallelism.

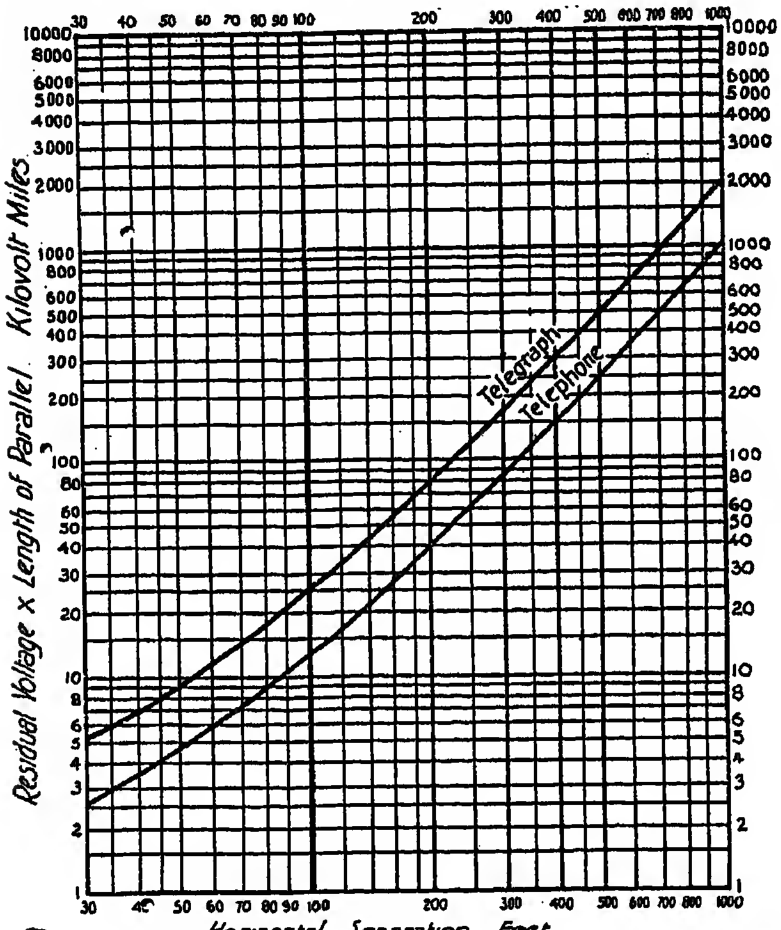


FIG. 23.—Residual voltage for parallels of 60-cycle, three-phase power lines and telephone or telegraph lines.

When the product of residual voltage (in kilovolts) and length of parallel (in miles) for a given horizontal separation exceeds the value given by the appropriate curve, interference may ordinarily be expected, under the assumptions given.

The charts referring to residual voltages and currents are given in Figs. 23 and 24. The figure for parallels involving telephone circuits is in the case of residual

TABLE 3.

Voltages between power conductors	Separation from highway and communication lines
	ft.
Below 50 000	600
50 000 to 75 000	750
75 000 to 100 000	850
100 000 to 150 000	1 000
150 000 to 200 000	1 200

voltages based on a value of the product of the length of parallel and the induced voltage between the conductors and earth of 150 volt-miles, and in the case of telegraphs of 300 volt-miles. In all cases referring to telephone circuits it is assumed that there are harmonics present which fall within the range harmful to speech. As an example of the use of Fig. 23 let it be assumed that it is proposed to parallel a telephone line over 10 miles at a separation of 60 ft. From the chart it is found that the value of the product of length of parallel and residual voltage corresponding to a horizontal separation of 60 ft. is 6 kilovolt-miles. Dividing by 10, the given length of parallel, the residual voltage permissible under the condition assumed is found to be 600 volts (effective value).

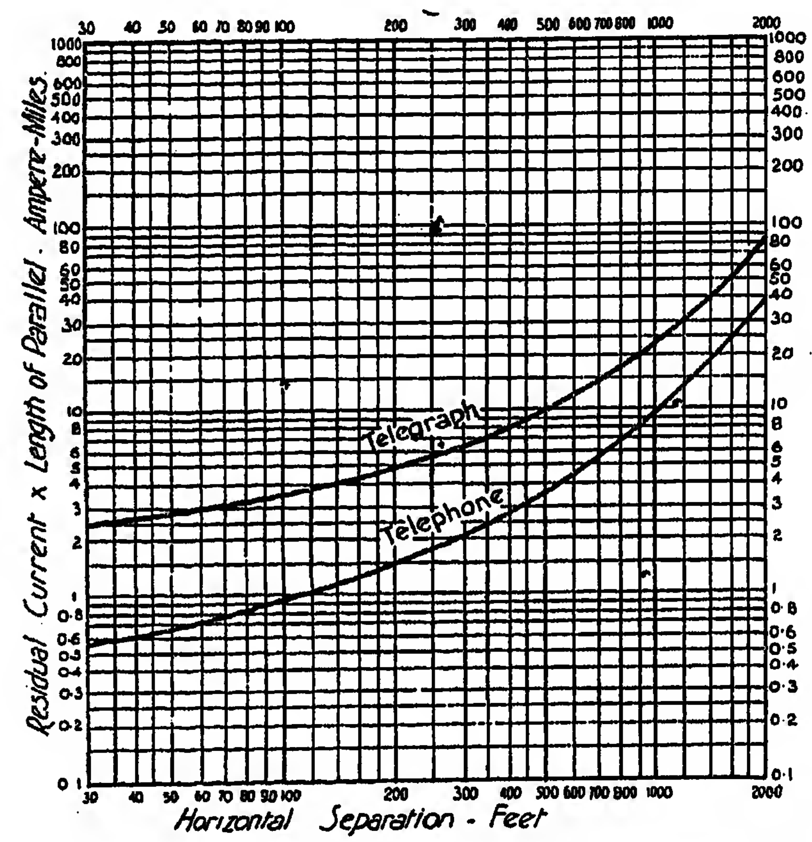


FIG. 24.—Residual current for parallels of 60-cycle, three-phase earthed-neutral power lines and telephone or telegraph lines.

When the product of residual current (in amperes) and length of parallel (in miles) for a given horizontal separation exceeds the value given by the appropriate curve, interference may ordinarily be expected, under the assumptions given.

In the case of residual current the curve is based on an induced voltage along the telephone conductors of 0·20 volt at 60 cycles per sec., and for telegraphs a value of 1 volt at 60 cycles.

As an example of the use of Fig. 24, assume that it is proposed to parallel a telephone line for 2 miles at a separation of 60 ft. with an earthed-neutral power circuit.

From the chart it is found that the value of residual ampere-miles corresponding to the horizontal separation of 60 ft. is 0·75. Dividing this by 2, the given length of parallel in miles, the residual current permissible under the conditions assumed is found to be 0·37 ampere (effective value).

Turning to the question of the clearance to be given to prevent the harmful effects of short-circuits, etc., in the *Elektrotechnische Zeitschrift* of 17th May, 1923, draft rules prepared by the Verband Deutscher Elektrotechniker are proposed for the protection of telephone

loop wires against influence by alternating-current systems. These rules lay down, *inter alia*, separating distances between power lines and telephone lines which are regarded as not dangerous should a power line be started up during the existence of an earth on the system. The values are shown in Table 4.

TABLE 4.

Up to 15 kV, more than 60 m.
Above 15 kV and up to 20 kV, more than 75 m.
Above 20 kV and up to 35 kV, more than 100 m.
Above 35 kV and up to 60 kV, more than 150 m.
Above 60 kV and up to 110 kV, more than 200 m.
Above 110 kV, more than 250 m.

The author does not know whether these rules have been approved.

The calculations in the case of single-phase electric railways where the power system is largely unbalanced have been made by various investigators. Here again, owing to the great number of factors involved, many of which are difficult to appraise, it is not easy to forecast on theoretical grounds what will be the result in any particular case. The current effects from such systems are usually the most troublesome and the amount of current returning in the earth path is the controlling factor, this naturally depending upon the measures taken to confine the current to the rails or to supplementary return conductors. If no special measures are taken, from 40 to 60 per cent of the current usually flows in the rails, the remainder returning via the earth.

Where communication circuits are erected at the side of a railway the track conditions usually limit the separating distance, and the physical conditions control the situation.

TELEPHONE CIRCUIT BALANCE.

The presence of power circuits in the vicinity of telephone circuits necessitates an unusually high standard of maintenance of the latter. Small defects that would cause little trouble were the power circuit non-existent, now prove annoyances of considerable magnitude, whilst apparatus that was thought to be accurately balanced is found to be wanting when exposed to the searching effects of strong fields. This is specially noticeable if the apparatus is earth-connected, as the capacity discharges through the apparatus will effectively show up any want of balance in the impedances. Further, it is possible to have trouble even if the exposed telephone circuit be perfect in balance as regards insulation, capacity and conductor resistance, and taken alone no disturbance is experienced, as this circuit is liable to be placed in connection with any number of other circuits any one of which may be more or less faulty. A faulty circuit at once introduces trouble in a violent form by unbalancing the combination. The trouble can be met to a certain extent by making all connections between the exposed circuit and others through transformers or repeating coils, as by this means an unbalanced circuit is prevented from upsetting the balance of the line subject to the interfering field. Such a procedure necessitates in some cases changes in the signalling arrangements, and there is always a certain loss in speech efficiency.

In all cases of inductive interference with telephones the first steps taken are to see that the circuits are properly balanced electrically. If a telephone circuit were perfectly balanced and transposed it would of course be possible for it to work undisturbed in any electrical field, but such a circuit is not obtained in practice. For a circuit to be perfectly balanced each leg of the loop should have the same series impedance, the same capacity and insulation resistance to earth, and the same capacity and insulation resistance to each other at all points. This is impossible in practice with overhead lines, and a properly balanced circuit for commercial purposes is taken as one which would be undisturbed by other telephone or telegraph circuits working on the same route. It follows that the better the balance of a telephone circuit the less likely is it to be disturbed, and the following points are looked into when trouble is experienced :—

Apparatus.—Listening tests are made directly on the lines, i.e. with all relays, repeating coils, etc., cut out. If the noise is reduced, the apparatus removed is examined. Standard apparatus is designed to be balanced to ordinary inductive effects when placed in a telephone circuit, but trouble may be introduced by the following defects :—

(*a*) Partial or intermittent contacts due to projections of solder on contacts and terminals of apparatus.
(*b*) Defective contacts in relays.
(*c*) Imperfect contacts at protective devices (fuses, heat coils and protectors).
(*d*) Badly soldered joints on frames or switchboards.

Line wires.—Methods of transposing line wires to prevent inductive interference in the case of telephone circuits have already been dealt with. The two wires of the loop should have the same series impedance; unequal resistance causes trouble, a difference of a few ohms being sufficient to accentuate interference. In making tests of resistance the circuit should be divided into sections which should be as short as practicable, as it is possible for inequalities of resistance to average out on a long length, but, nevertheless, the local unbalance will cause a circuit to be noisy. Where unbalance is detected, all connections should be examined for dry joints.

Insulation.—Insulation balance is of great importance, and noise may be due to local differences of insulation where a test of the whole line shows no great disparity. This is especially so if the whole insulation is low, as there may be great local differences which have considerable noise effect. When the insulation is high the local unbalances are not likely to be considerable.

Where insulation is not up to standard careful line inspections should be made. Defective insulators and partial contacts caused by trees or debris should be removed. Protective fittings should also be examined.

When the circuit is partly in cable, listening tests should be made with the cable sections in and out of circuit, and it should then be possible to ascertain whether the insulation of the cable is a factor in the unbalance.

Inductive effects are sometimes experienced in circuits not directly affected by power circuits, owing to their proximity in a cable to circuits which are affected. In one instance the circuits comprising a great part of a telephone exchange were very badly disturbed following the commencement of electric traction on a railway, yet none of the circuits disturbed was close to the railway. The cause of the trouble was traced to a telegraph circuit which ran adjacent to the electric railway for a portion of its route and for another small portion in the cable in which there were also telephone circuits terminating at the exchange. Inductive effects from the railway power line were thus carried over a wide area by the telegraph line and telephone circuits following the common route for a short distance.

Methods for Minimizing Telephone and Telegraph Interference.

Remedies applied to telephone circuits.—Various methods have been devised for reducing the effects of induction upon telephone circuits by modifications or alterations in the apparatus. In the early days when single-wire telephone circuits were more common and relatively short, some kind of success was achieved by methods which reduced the sensitivity of the circuit. One of these was to increase the clearance between the diaphragm and the coils of the receiver by inserting a brass ring. This made the noise less offensive, but it of course reduced the volume of speech and was only a palliative dependent for success on the circuit having a good speech margin. In some instances a condenser placed across the receiver was effective.

A rather more elaborate arrangement was one in which impedance coils were joined in the circuit to choke out the interfering currents, and incidentally the speech currents, and then improvement was made in the latter by increasing the transmitter voltage; this met with a fair amount of success, but it had the drawback that the increase in working voltage caused overhearing in neighbouring circuits.

Specially designed loud-speaking telephones used on circuits deliberately made insensitive by capacity-coupling connections have answered in some cases.

Endeavours to shunt the interfering note by means of tuned inductance and capacity have not been very successful. The note to be removed is generally composite and, even if well defined, is of a frequency that falls within the vital speech range, and speech in its removal is degraded.

It is important to bear in mind that none of these methods is suitable for public telephone circuits—the most that can be claimed for them to-day is that they may be of use in dealing with private lines, e.g. between collieries, etc., of which there are still no doubt many left in the country.

The coupling of the power circuit with the telephone line at a transformer has been suggested at various times. One early reference is given in Hopkins's "Telephone Lines and their Properties," published in 1898. The connection of the windings on the transformer is such that the current induced in the transformer is 180° out of phase with that induced in the line section of the circuit. A development of this by Mr. J. Sayers is referred to later in the section on single-phase railways.

A more modern development is attributed to Marius Latour. The telephone current is amplified for transmission and in the terminal apparatus the strength of this current is brought down to the value corresponding to normal audition, which at the same time reduces the intensity of the disturbing current. The amplification can be regulated as required at the transmitting end, and the disturbing effect can be reduced to a value sufficiently low as not to interfere with telephone conversation. Ordinary vacuum-tube amplifiers are employed. Such an arrangement would be satisfactory on single-circuit routes, but overhearing would occur on lines carrying two or more circuits, owing to the greater power used.

Remedies applied to telegraph circuits.—It is possible to reduce within certain limits the inductive effects on the working of telegraph apparatus. Telegraphs are usually only affected by currents of the fundamental frequencies in the case of power-transmission lines, and by the fundamental electromagnetic effects in the case of single-phase railways, these frequencies being within the working range of such apparatus. It has been the last-named effects which have caused most trouble and have, in consequence, led to the trial and application of remedial measures. Telegraph circuits are, in the great majority of cases, worked with an earth return. The types of apparatus are numerous, depending upon the service required, the speed of working varying from 20 to, say, 200 words per minute, although speeds as high as 600 words per minute can be attained under suitable conditions. By duplexing, quadruplexing and multiplexing, it is possible to provide from 2 to 12 channels by means of one wire. The currents required to operate the different telegraph apparatus when worked directly in a line, i.e. short-distance circuits, varies between 1 mA for a polarized sounder to 69 mA for the old-fashioned inker. Where the actual telegraph apparatus is worked from relays, the minimum current required to work the relays varies between 0·5 mA for the most sensitive, up to 6 mA. For very high speeds, however, some of the relays require a larger minimum current, according to type, but much smaller currents will interfere with the working.

It will be gathered from this that very small foreign currents are likely to mutilate telegraph signals.

The highest pressure employed on telegraph circuits in this country is 120 volts. Somewhat higher pressures are used in some other countries. The voltage employed depends upon the length of line and the apparatus in the circuit. The magnitude of the interference effects will therefore depend not only upon the foreign voltage impressed on the circuit, but to a certain extent also upon the frequency of the interfering current and the speed or number of words per minute at which the telegraph circuit is operating. Trouble may result in some cases when a foreign voltage as low as 10 per cent of the working voltage is impressed upon the circuit. The higher the speed of the telegraph working, the more likely it is to be mutilated. The length of the marking signal or the time the marking current is flowing depends upon the speed, and at low speeds a portion of this

length can be lost without interference with the signal, i.e. there is enough effective current left to produce the signal. At high speeds, however, the time the marking current is flowing is reduced and, as further clipping cannot be tolerated, interference which may be unnoticed at low speeds is sufficient to cause faulty reception.

The remedies that can be applied depend upon the values of the induced voltages. With the very high induced voltages experienced in America, very special steps had to be taken to reduce these by employing neutralizing transformers in the communication circuits. These are referred to in the section dealing with single-phase railways. The most successful remedies have been those based on the fact that telegraph apparatus is inserting an inductive resistance which has a high effective value at the frequency of the interfering current but a relatively small one with direct current.

Slight perturbations have been prevented in relays by the provision of a copper tube between the electro-magnet and the windings. This damps out the high-frequency effects.

The greatest success has been achieved with resonant shunts. Fig. 25 shows the application of such shunts to duplex and simplex telegraph circuits in this country. The shunt is based on the well-known resonant formula, and for a frequency of 25 has a capacity of $0 \cdot 2\ \mu F$ and an inductance of $20 \cdot 05$ henrys. There are disadvantages with high capacity or high inductance. If a high capacity is employed it will seriously reduce the

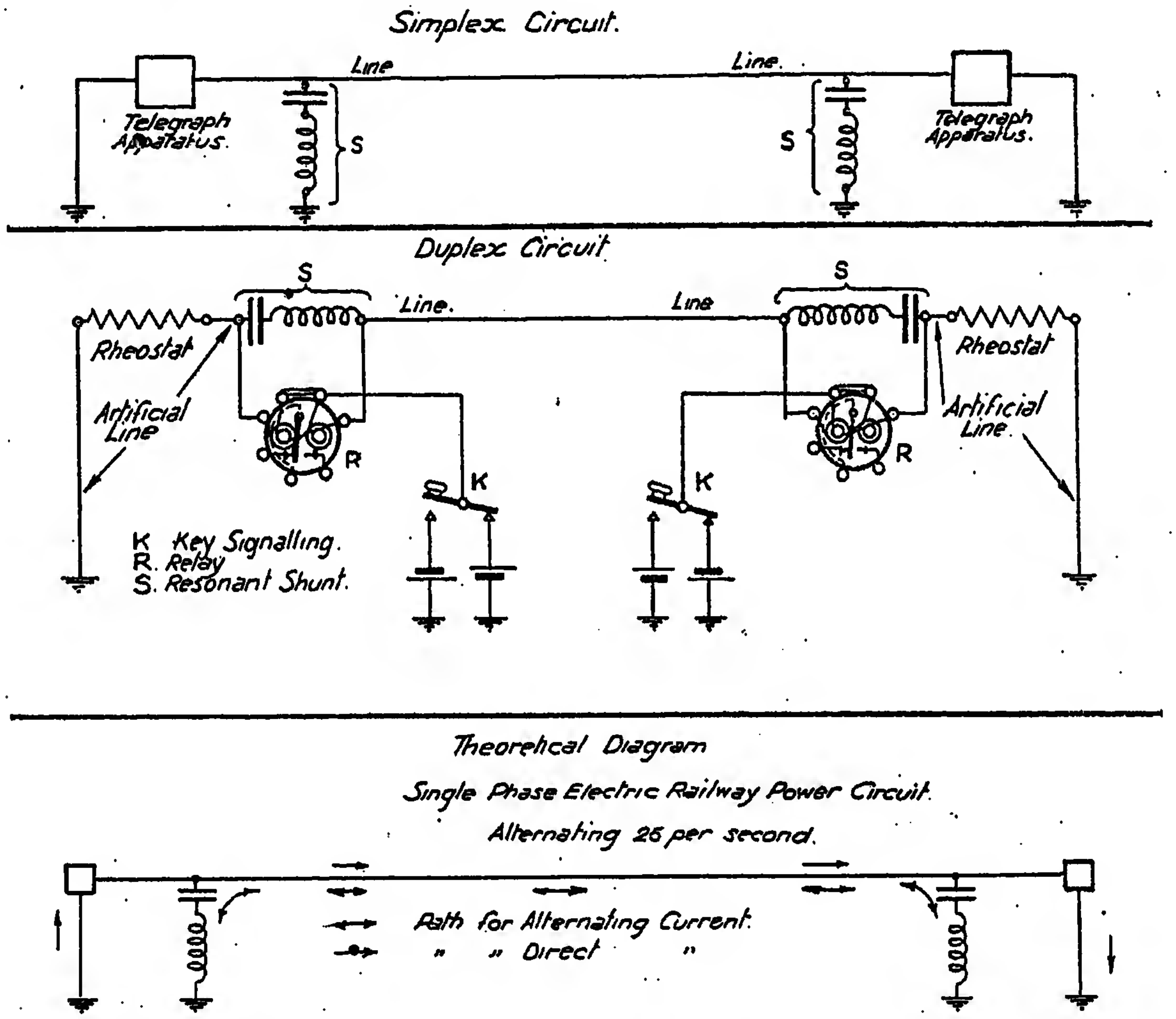


FIG. 25.—Resonant shunts applied to telegraph circuits.

usually worked with direct current, and as the interfering current is alternating it is possible to arrange for the alternating current an easy path which is closed to the direct current, and, further, to arrange a path which is closed to the alternating current but open to the direct. There are, however, a few other methods which may be applied where the interference is not excessive, e.g. resistance can be added to the circuit and the working voltage increased. This has a limited application, as the induced voltages are usually high and to overcome them would require excessive working voltages. Moreover, a higher working voltage than the normal will cause interference between telegraph circuits themselves.

Interference with signalling systems where direct current is used can be overcome in some cases by signals on certain types of circuit which are worked with condenser impulses, whilst a high inductance involves a high resistance to produce the inductance, unless considerable iron is used with the coil; and a high resistance will defeat the object of the shunt. Again, if iron is used the inductance will vary with the current passing and the shunt will cease to be resonant at all values of current. It can be said, however, that it is possible by means of these shunts to make certain circuits workable which would otherwise be unfit for use. Their use is limited, however, to circuits worked at hand speed, as with automatic working at certain speeds the signals are distorted owing to the shunt coming into action and providing a path for the working current. With a shunt fitted to Wheatstone apparatus good signals are obtained until a speed is reached which,

in effect, results in alternations approaching the frequency of the shunt or multiples of the same. For instance, on a Wheatstone circuit there will be good

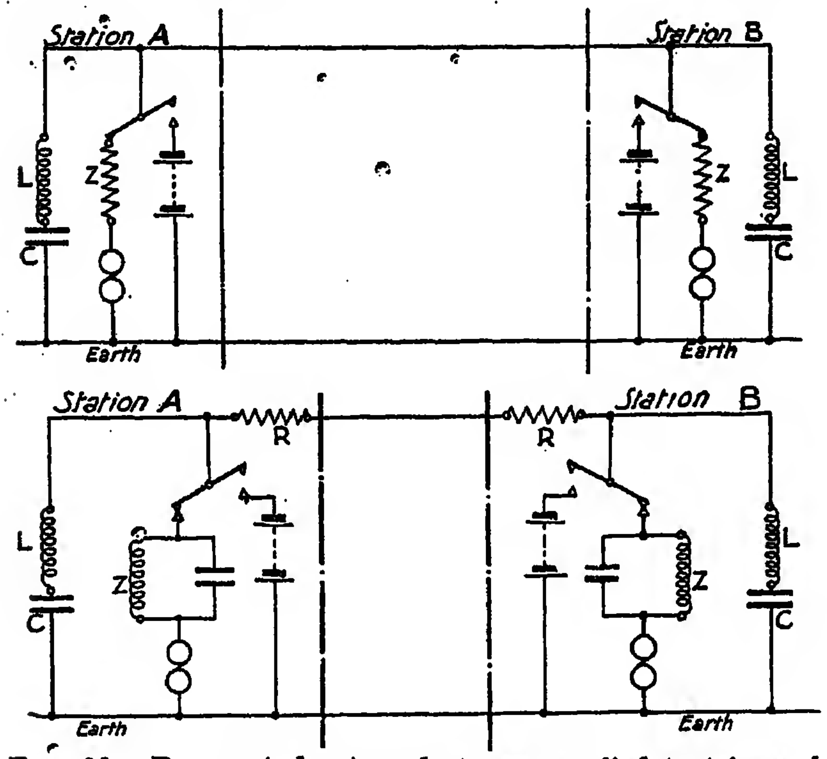


FIG. 26.—Resonant shunts and stopper applied to telegraph circuits.

signals up to 50 words per minute, but between 55 and 80 words per minute they are badly broken up. After that the signals are again good until a frequency multiple of 55 words is reached. Wheatstone working at 55 words per minute is roughly a periodicity of 25 per second.

As regards the actual prevention of interference, these methods naturally fail if the induced voltage is very high. In an actual case of a circuit fitted with a shunt and working with a 50-volt battery an induced pressure of 22 volts was sufficient to interfere with the operation.

M. Latour, in a communication on H. S. Warren's paper,* describes the application of the same kind of shunt with improvements in the shape of a stopper circuit in the telegraph instrument path. His first and final arrangements are shown in Fig. 26. In the last Z is the stopper, i.e. the capacity and inductance in parallel having the same values as those required for resonance. The application was made to telegraph circuits subject to influence by a single-phase railway working at a frequency of $16\frac{2}{3}$ per second, the values being 50 henrys and 2 μF.

Other palliative arrangements are shown in Fig. 27, and these are self-explanatory. It should be borne in mind that all the remedies referred to are for use with single-wire telegraph circuits. A double-wire circuit should not require devices of this character.

TRACING THE SOURCE OF THE INTERFERENCE.

Tracing the source of a disturbance may present difficulties where a circuit passes through many power areas. The simplest method is to go over the route with a search coil and a telephone receiver, listening at the likeliest spots and comparing the pitch of the note with that heard on the actual telephone circuit. Search coils can be made up in many forms. The most effective is that in which the impedance of the coil itself is equal to the impedance of the receiver, which in practice means that a low-resistance receiver should be used with a coil of few turns, and a high-resistance receiver with a coil of many turns.

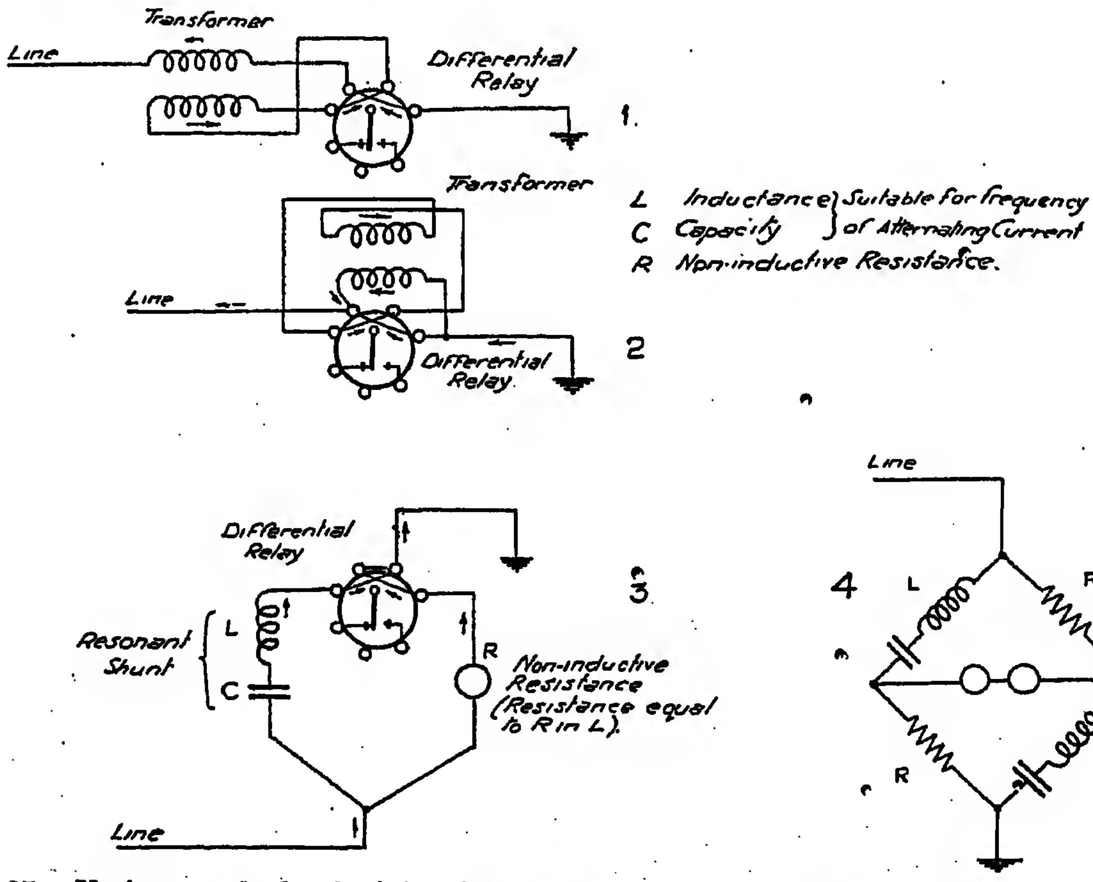


FIG. 27.—Various methods of minimizing effects of alternating current on telegraph circuits.

* *Transactions of the American Institute of Electrical Engineers*, 1918, vol. 37 p. 503.

If more than one system gives the same note, which is not an unlikely contingency, then it may be necessary to shut down one or other of the systems specially to find the offender.

The frequency of a ripple can be obtained fairly accurately by comparing the pitch of the note heard on the telephone with that of a tuning fork, pipes, or a piano. The pitch of all pianos is not based on a common fundamental frequency, however, and the accuracy of the comparison of the pitch of notes depends upon the musical faculties of the individual making the test, and observers differ unless they have specially trained hearing. It is possible to ascertain accurately the frequency of a ripple by means of apparatus that impresses a note which can be varied, and the frequency of which is known, on the same circuit as that having the unknown note; synchronism can be ascertained by the beats, or rather the intervals between the beats. Fig. 28 illustrates such an arrangement diagrammatically.

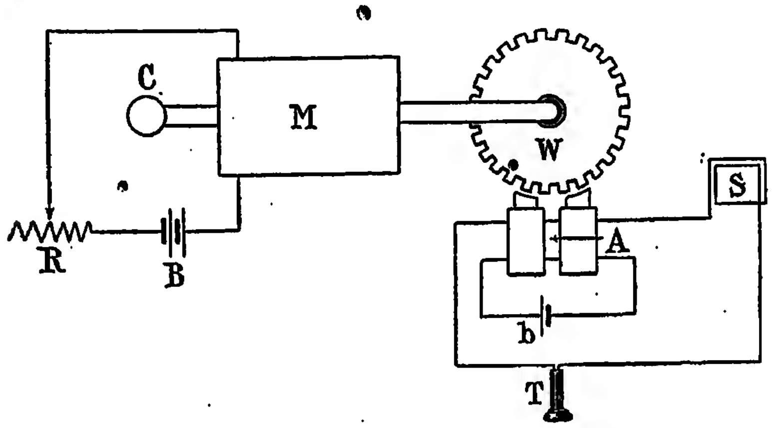


FIG. 28.—Method of ascertaining pitch of note.

M = Motor.
R = Resistance (adjustable).
B = Battery (100-volt).
W = Cog-wheel, 60 teeth.
A = Stator of alternator (2 poles).
b = 1 cell.
C = Counter.
S = Search coil or telephone circuit.
T = Telephone receiver.

The motor, the speed of which can be varied by means of the adjustable resistance, drives a cog-wheel having 60 teeth, the rim of the wheel being so placed that it acts as the rotor of a small alternator, the stator of which consists of two poles, the field being supplied by a single dry cell. As the cog-wheel revolves, the teeth cut the field at the same periodicity per second as the motor speed per minute. The speed per minute of the motor is obtained from a counter on the armature, and it is possible, therefore, by noting this figure to know the frequency of the note produced by the alternator. When, by adjustment of the resistance, the alternator note approaches the frequency of the note under test, beats are heard which become separated by longer intervals as the notes come into synchronism. When this point is reached, the counter figure gives the information required. This method was employed by Prof. Miles Walker in some investigations in which the Post Office was concerned.

The Problem as Affecting Different Power Systems.

It is now proposed to deal more specifically with the different types of power circuits as used commercially in this country, viz. tramways, railways, and electric light and power circuits, indicating in a general way the steps taken to overcome interference, and any other features that may be of interest in connection with the matter under consideration.

Tramways.—The most usual system employed in this country is the single trolley wire with an insulated rail return. There are a few miles of track in the neighbourhood of Greenwich Observatory where double trolley wires are used. In London the conduit system with positive and negative conductors is common.

Interference with telegraphs by stray currents is likely to occur where an uninsulated rail return is employed. The Ministry of Transport Regulations limit the difference of potential between any two points on the uninsulated return to 7 volts. This has an important bearing on interference with telegraphs and the signalling on telephone circuits. Trouble does not usually occur where this regulation is complied with. If the undertaking is working within the limits laid down, it is usual to apply the remedy to the telegraph or telephone circuits. Trouble can usually be overcome by artificially increasing the resistance of the circuit so as to reduce the strength of the foreign current. Incidentally, this may of course involve increased battery power for the operation of the apparatus. A change in the earth connections may be effective; for instance, use of earth plates instead of connections to water pipes may be desirable, especially if the tramway negative busbar is earthed on a water main.

The currents and voltages in the usual tramway system with uninsulated rail return are totally residual, but as the current is direct, one would not anticipate trouble from induction, and, in fact, that was the experience until a few years ago when the rotary converter came into general favour. The earlier types of rotary converter did not, however, cause trouble. It is not for the author to explain this, but, superficially, one is struck with the great difference in size for the same output, and the greater air-gaps in the older and larger machines. It would seem that the general overall increase in efficiency brought, as usual, an evil in its train. In passing, it may be remarked as a strange development that in recent years there has been more interference trouble on this account from d.c. systems than from a.c. systems, which is a warning to those inclined to prophesy.

As explained earlier, harmonics are produced in d.c. as well as in a.c. systems. In the case of tramways there are two kinds of high-frequency pulsations which may affect the neighbouring telephone circuits. One of these, (*a*), is produced by the motor on the car, and results in a varying note being heard in the telephone receiver as the car gathers speed; whilst the other, (*b*), originates in the machine supplying the current and produces a constant note of high pitch in the telephone receiver.

In the case of (*a*), the disturbance is likely to be more intense if the bonding of the tramway rails is not in good order, and is more marked on systems where the trolley wires carry the whole of the current without supplementary underground feeders. Interference is not usually great unless the telephone wires and the tramway

run parallel for a considerable distance. In such cases good balance of the telephone circuits is essential in order to reduce the interference.

As regards (*b*), the effect upon the telephone service is more serious, as a strong disturbing field is sometimes produced, which may be detected at a considerable distance from the tramway system. The machine producing the disturbance is usually the rotary converter, and the causes and some remedies which may be applied to the machine are referred to on page 828.

If the tramway system is extensive, with substations feeding the system in common, the disturbance is usually more severe owing to balancing current constantly flowing in the trolley wires and feeders between the substations. Improvement will usually result if the substations work independently, i.e. if each substation feeds a portion of the system and there is no connection with other portions.

If the tramway undertaking has a stand-by battery at the station, the inductive disturbance will be reduced by placing the battery across the offending machine (see Fig. 29). The battery affords a low-resistance path for the ripples and, in addition, will tend to flatten the ripple in the external circuit by resisting changes due to the rise and fall in the voltage of the ripple. This method is not effective if there is an automatic booster machine in the battery connection.

If the ripple is of a well-defined frequency it should be possible to shunt it at the machine by an arrangement of capacity and inductance tuned to the frequency of the ripple (see Fig. 30). If the capacity and inductance are of the correct values the shunt will form a low-resistance path for the ripples, whilst affording no path for the d.c. supply to the system. The author tried this method experimentally some years ago with a certain amount of success, but the best results were obtained when a choke coil was added between the machine and the busbar. This method is similar to that described for use with mercury-arc rectifiers by Prof. Marchant in the appendix to this paper. It is understood that it is also used successfully in America. The best values for C (capacity) and L (inductance) are those which provide a resonant circuit, and this is obtained when

$$n \text{ (frequency of the ripple)} = 1/[2\pi\sqrt{(CL)}]$$

With these conditions the resistance of the shunt to the ripple will be the simple ohmic resistance in the shunt, and the effectiveness of the shunt will therefore depend on that being kept low.

Electric railways.—The electric railways of this country are in the majority of cases worked with direct current, exceptions being a short section of the London, Midland and Scottish Railway between Lancaster, Morecambe and Heysham, and a portion of the Brighton section of the Southern Railway in the London district.

Direct-current railways.—The conditions giving rise to interference are electrically comparable with electric tramways. There are, however, in this country relatively more systems using insulated returns, and with such systems interference by leakage and induction is not so likely to occur. On most of the systems a medium pressure is employed, viz. 550–600 volts, but there are two cases where a higher voltage is used. The London and North-Eastern Railway employs a 1 500-volt overhead contact system on a mineral railway between Shildon and Newport, near Stockton, whilst the L.M. and S. Railway employs between Manchester and Bury a contact rail at a pressure of 1 200 volts.

As railway tracks are usually well drained and the rails are on sleepers, leakage currents should be less

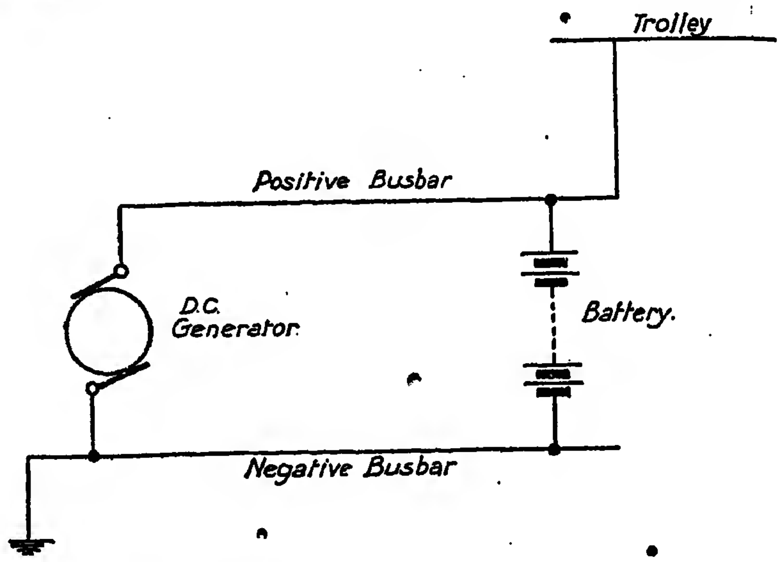


FIG. 29.—Shunting harmonic by means of stand-by battery.

than on tramway systems on public roads. Against this, however, has to be set the fact that some electric railway systems are not specifically limited by Ministry of Transport regulations as to voltage drop in the rails. The Ministry of Transport regulations referring to electric railways in metal-lined tubes limit the fall of potential in the uninsulated rail to 7 volts.

In the early days of tube working in London, a certain amount of trouble was caused to telegraph circuits. It

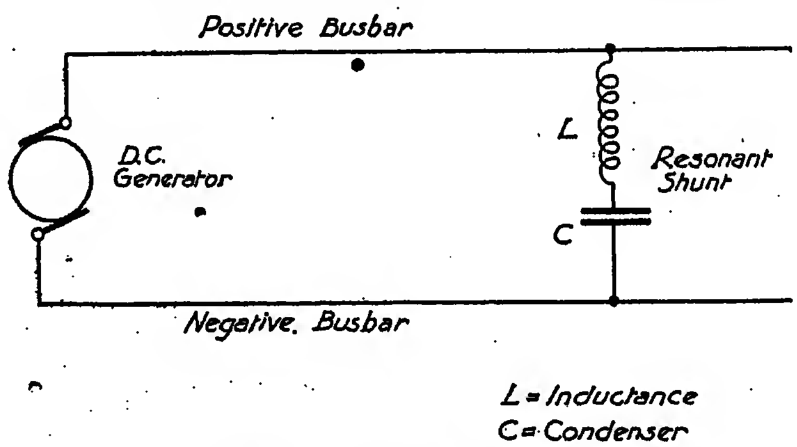


FIG. 30.—Resonant shunt across d.c. machine.

was found necessary to insert resistances in the lines and consequently to increase the battery voltages. In the case of the City and South London Railway, great improvement came with a change in the method of working to what is practically the same as the 3-wire system of electric light distribution, the live rails on the two tracks being the outer conductors, with the running rails as the neutral.

The great increase in the extent of electric railways in London has not brought about a corresponding increase in disturbance to telegraphs, and the author attributes this to the fact that, coincident with this

development, the Post Office brought the high-resistance polarized sounder into general use in London.

There was a certain amount of interference with fire-alarm circuits when the Metropolitan Railway electrification commenced in 1905, but this was overcome by changes in the earthing arrangements and by increasing the resistance of each circuit. The faults caused were more numerous when the first experimental trains were run, and, no doubt, certain weaknesses were removed on the railways as time went on.

Inductive effects will be influenced by the type of lay-out of the system. With the third-rail contact system in which the ordinary running rails are used for the return current the effects will generally be the same as with the tramway systems, modified by the fact that there will be less leakage to earth on a well-drained railway track, tending to produce less out-of-balance electromagnetically, and by the close proximity of the positive conductor to the earth surface reducing the electrostatic effects.

With the overhead contact system the conditions approximate to those of the street tramway systems except that the leakage currents should be less. In the case of railways using the fourth rail the system is more nearly balanced electrically and should be better from the point of view of interference.

Rotary converters are generally used for supplying direct current, and methods of reducing the harmonics produced by such machines have already been described. A certain amount of trouble has been caused by interference with telephones by d.c. railways employing rotary converters, and machines have had to be altered to overcome the interference.

The telephone circuits in these cases run alongside the track for a few miles with a relatively small distance separating them from the live rails and cables. The alterations to the machines to reduce the harmonics have resulted in the circuits being made workable with the telephone lines in good balance, but slight faults which previously would not have affected the working to any extent now make the conditions intolerable. To that extent the maintenance costs are increased, and, in addition, loss is incurred owing to the circuits being more frequently thrown out of use and having their earning power reduced.

Single-phase systems.—It is not for the author to take part in the old controversy of direct-current versus single-phase traction in its efficiency aspect, but one cannot avoid making certain comparisons between the two systems where interference with communication circuits is concerned.

The direct-current system, as developed in recent years, has certainly produced unpleasant and unexpected features in this respect, but undoubtedly the general experience with single-phase railways in many countries has shown that system to be the worse offender. The lay-out of the system has a most important bearing in this connection and many varying methods have been adopted, some of which will be described. It is difficult to obtain in all cases definite particulars of all the results in this respect, and there is some conflict of evidence. In some cases complete success in overcoming trouble is claimed, whilst, on the other hand, statements of a pessimistic character have appeared. An instance of the latter is an article by Zehme in the *Electrical World* of 5th March, 1921, which calls attention to the doubts in Germany as to the advisability of selecting the single-phase system for all German lines, especially in view of the induced voltage of 4 000 which was found to be rapidly destroying the signal cables on the Silesian mountain road. Further, a Swedish Commission reported against the alternating-current system and the Swedish Riksdag approved the plans of the new railway from Stockholm to Gothenburg only on condition that a satisfactory solution of all inductive disturbance should be found. On the other hand, there is a statement in M. Bachellery's recent paper* on "The Electrification of the French Midi Railway," to the effect that in the section experimentally operated on the single-phase system it was possible by taking apparently simple steps to work the communication circuits quite satisfactorily.

However that may be, the use of this system of traction is considerable. In Germany it is in favour and in Switzerland the system is very successfully used. In America the New York, New Haven and Hartford Railway is the principal railway working on the single-phase system, and a great deal of information on the results of the working of that railway has been published. The author has first-hand information on the inductive effects of the Lancaster–Heysham section of the London, Midland and Scottish Railway and of the more extensive Brighton section of the Southern Railway. Before giving details of the various experiences, he proposes to indicate briefly the conditions of working and the electrical arrangements which affect the question of interference. As members are aware, alternating current is supplied at extra-high pressure, usually at a periodicity of $16\frac{2}{3}$ or 25 per second, into an overhead contact wire fixed above and parallel with the track rails at a height of about 16 ft. The current is fed through a bow collector to a transformer on the train and from this returns through the motors to the source of supply via the wheels, rails and earth, and in some cases through subsidiary cables or wires. The effects upon neighbouring communication circuits can be summarized as follows :—

(*a*) Due to earth currents or leakage from the track rails;

(*b*) Electromagnetic induction from the trolley wires, track rails and (if any such are provided) conductors in the cables at the side of the track; and

(*c*) Electrostatic induction from the trolley wires.

(*a*) Earth or leakage currents are likely to be greater than with a direct-current system, as the impedance of steel rails is greater with alternating current. The Ministry of Transport do not appear to have laid down regulations as regards voltage-drop on the uninsulated rail return for this type of railway. A drop of 20 volts has been suggested as a reasonable figure, but it is a difficult matter to ascertain what the actual drop on the rails really is, as a reading, if made in the ordinary way, would include in addition to leakage the inductive effects of the system upon the testing leads and upon

* *Journal I.E.E.*, 1924, vol. 62, p. 213.

the rails and pipes in the ground near the track. It is possible partly to avoid these effects in the testing leads by using wires running nearly at right angles to the track with a long loop, but as regards rails and pipes it is a much more difficult matter, as the testing wires will form a closed path for the currents induced in the earthed bodies, and the direction of the current will be in opposition to the leakage current.

(*b*) Electromagnetic induction is the most serious feature of this system of traction. The power system of this type of railway is totally unbalanced in the case of the simple lay-out described later, and to some extent whatever precautions are taken. The fundamental frequency of the alternating current, which is usually 25, is such as to affect telegraphs, and it is generally telegraphs which are most seriously disturbed.

(*c*) The trolley wires being charged to a high potential, alternately positive and negative, produce static inductive effects or electric charges in all neighbouring open wires. The effects are reduced if there are earthed structures or wires in the vicinity of the overhead power conductors or of the communication circuits.

The results of induction or leakage to be expected theoretically have been worked out by a number of horizontal separations between the trolley and the communication circuit and the different percentages of the trolley current in the rails. For example, it has been determined that with 60 per cent rail current, that is, 40 per cent of the trolley current return flowing in the earth as stray current, the induced voltages per mile per 100 amperes in the trolley are in general about 10 volts, 5 volts and 1 volt, at 50 ft., 300 ft. and 1 000 ft. separation respectively. Thus at 50 ft. separation with 1 000 amperes in the trolley a 10-mile exposure would result in an induced pressure of 1 000 volts. These are maximum figures, in that they are based on the assumption that power is supplied in one direction only.

The worst conditions occur when the system has a simple lay-out, shown in Fig. 31, where the power system is quite unbalanced. Examples of this type of working are the Lancaster–Morecambe–Heysham section of the L.M. and S. Railway, the original New York, New Haven and Hartford Railway in the U.S.A., and others on the Continent. Experience with the system led subsequently to the introduction of modifications in the lay-out of the New York, New Haven and Hartford Railway and, it is believed, of many of the Continental lines.

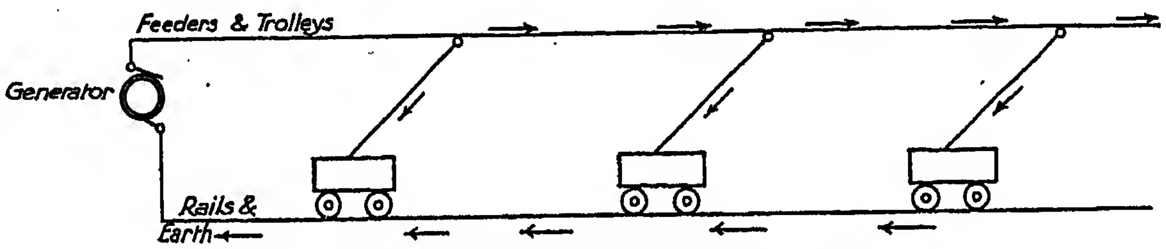


FIG. 31.—Single-phase system—simple lay-out.

investigators, but, as in all these cases of interference, the assumptions are many and the treatment is complicated by the very numerous factors. The electrostatic effects are very considerably modified by the presence of earthed bodies, wires, etc., in the neighbourhood of the power circuit and the communication circuit under review, and the electromagnetic effects are similarly greatly influenced by the amount of current straying from the rails. Where calculations have been made, however, very fair agreement with actual effects has been recorded. Such a comparison between theory and practical results is given in the *Elektrotechnische Zeitschrift* of the 6th, 13th and 20th May, 1915, in a communication from O. Brauns of the German Telegraphs Test Office on the disturbances to telegraphs in the neighbourhood of the Albtal Railway, the Wiesental Railway and the Dessau–Bitterfeld Railway. A most informative paper on the effects of a.c. railroads on communication circuits, by H. S. Warren, is contained in the *Transactions* of the American Institute (1918, vol. 37, p. 503). This gives particulars of the effects produced by four important American railway electrifications on telegraph and telephone circuits, and, whilst many of the effects are very serious, Mr. Warren is not pessimistic even as to the reduction of the excessive interference during abnormal conditions on such railways. As indicating the values of induced voltages, Mr. Warren takes 100 amperes in the trolley wire for different

It may be of interest if a few figures are given which indicate generally the effects experienced on circuits running parallel with the New York–Hartford line. In one case on a length of 23 miles, with a separation varying between 100 and 5 600 ft., the circuits had pressures of 300 volts induced in them. Circuits in cables situated from 300 to 5 600 ft. from the railway and roughly parallel for 25 miles had 170 volts induced at times of heavy load. Even a line 4–5 miles distant and parallel for 30 miles had induced pressures of 40 volts. In addition to the above voltages which were produced by the fundamental current of 25 frequency, there were higher frequencies produced by the motors when the trains were running, and these had a serious effect on the telephone circuits. When short-circuits occur between the railway trolley wires and the rails the voltages induced in the communication circuits reach values much larger than under normal conditions. These higher voltages operate the protectors and ring the subscribers' bells.

To overcome the large induced voltages, "neutralizing transformers" have been used on the telegraph and telephone circuits, with fairly satisfactory results. The application of these neutralizing transformers is based on C. F. Scott's patent specifications Nos. 14752–3/1907. Fig. 32 illustrates the underlying principle. The transformers contain either 18 secondary pairs and 8 primary pairs, or 22 secondary pairs and 8 primary pairs. The

wires joined to the primary coils are earthed at each end of the route or section exposed to the influence of the electric railway, and it is arranged that the induced effects of the primary wires tend to neutralize through the transformer the induced effect of the power circuits on the secondary circuits, that is, the circuits to be protected. The transformers are so designed that at a frequency of 25 cycles per second, and with a normal E.M.F. induced by the railway power circuit, an induced potential of 75 volts is produced on the secondary circuits opposing that due to the railway circuit. By arranging for a sufficient number of these transformers in series, it is therefore possible to nullify any induced potentials, each transformer disposing of 75 volts. The transformers give a transmission loss on all telephone circuits to which they are connected. This amounts with three transformers in a circuit to 0·6 mile of standard cable. It is stated that there is no appreciable "cross-fire" between the telegraph circuits working on the transformers, which will probably be the case with circuits worked at hand speed, but it is doubtful whether high-speed working would not be affected. It should be noted that the transformers are effective only in reducing voltage effects and have yielded no improvement in respect of the high-frequency noise on the telephone circuits. The transformers are very weighty, the heaviest type weighing about 1 500 lb., and they have to be protected by lightning arresters, which give considerable trouble. The railway company subsequently altered their system of distribution, and details of this are given later in the paper.

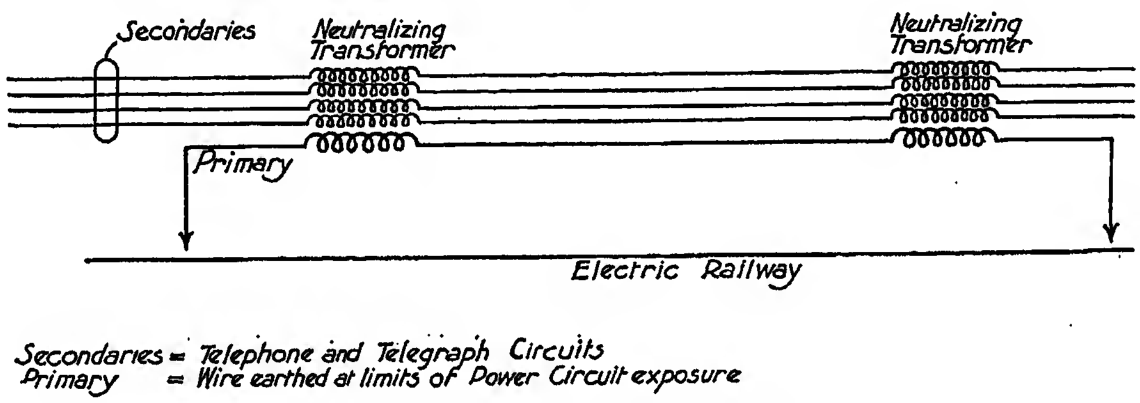


FIG. 32.—Neutralizing transformers.

The original single-phase railway between Dessau and Bitterfeld, Germany, was also worked with the simple lay-out referred to, a voltage of 15 000 at a frequency of $16\frac{2}{3}$ per second being employed. With the commencement of working, the telegraph line in the vicinity carrying foreign circuit could not be used, the circuits having to be diverted to other routes. Some tests made on the abandoned wires by O. Brauns are of interest. From the observed tests it was shown that with a 25 miles' exposure, and with full load on the power line, a voltage of 800 would be induced in neighbouring telegraph circuits. With a moderate load, 250 volts was actually measured, and to quote from a translation of an article on the subject: "It is consequently no longer remarkable that arc lamps which were connected to the wires at the Dessau Telegraph Office burned well."

The results of subsequent investigations on other wires in the neighbourhood as to the neutralizing effects produced by earthed wires and negative boosters are given in the paper in the *Elektrotechnische Zeitschrift* previously referred to. The amount of current found to stray from the rails varied in the three railways, it being 65 per cent on the Albtal Railway, 40 per cent on the Wiestental Railway, and 36 per cent on the Bitterfeld line. By the use of an earthed wire with an impressed "reverse" voltage, i.e. a voltage 180 degrees out of phase with the trolley wire, the electrical effect on a neighbouring wire, as measured by the charging current, showed a reduction of 53·7 milliamperes to 3·95 milliamperes, i.e. a reduction to 7·4 per cent.

As regards electromagnetic induction, it was found that wires in cable were affected to the same extent as open wires at equal distances from the rails. On the wires running parallel to the Bitterfeld railway for 22 km, with 100 amperes in the trolley wires the induced voltage varied between 90 and 95 volts according to the position of the wires on the arms. Four booster transformers of a type described later were provided to reduce the current straying from the track. This had the effect of reducing the induced voltage to between 5 and 19 per cent of the previous figures, according to the position of the train in the booster section.

The single-phase line on the London, Midland and Scottish Railway between Lancaster, Morecambe and Heysham was opened in 1908. The system is worked with a voltage of 6 000 to 7 000 at a frequency of 25, and the simple lay-out is employed, the feed being into the trolley wire with a rail return. The rails are connected to earth plates in the River Lune at Lancaster and in the sea at Morecambe and Heysham. It is stated that recording instruments in these earth connections have not indicated any current passing to earth. The Post Office had a few wires on the railway, the greatest exposure being a distance of about 3·5 miles. A number of tests made showed that the electromagnetic effect resulted in a pressure of 13 volts being induced in these circuits. This was at a time of light load and would no doubt be considerably higher with heavy traffic. There was a certain amount of interference with the telegraphs, but it was found possible to bias the instruments so that they work satisfactorily.

Some interesting experiments were carried out in co-operation with the railway company's engineers. In

the first case tests were taken to ascertain what actual loss of speech was occasioned by the noise induced in a telephone circuit by the railway. It was found that a telephone circuit running for a portion of its route on the railway had a speech value of 7 miles of standard cable with the railway not working. This was increased to 18 miles of standard cable with the railway in operation, i.e. there was a loss of 11 miles in audibility owing to the inductive effects of the railway. The wires of the circuit concerned were not twisted, however, and the railway company erected a properly revolved loop to ascertain whether the trouble could be overcome by that means. The experimental loop was found to be noisy, although the wires were properly regulated. With the railway not working, the circuit had a standard cable measurement of one mile; and with the railway working this was increased to 8·8 miles.

Another point was also investigated at the same time by the aid of this specially erected line. That was to ascertain what reduction in the electrostatic effects was produced by earthed wires in the neighbourhood. The railway company had provided an earthed wire between the contact wire and the telegraph route for this purpose. The position of affairs is shown in Fig. 33, which also indicates the position of the specially erected experimental line. The effect of this earthed wire, combined with that of the earthed telegraphs on the same line as the circuit under test, resulted in a

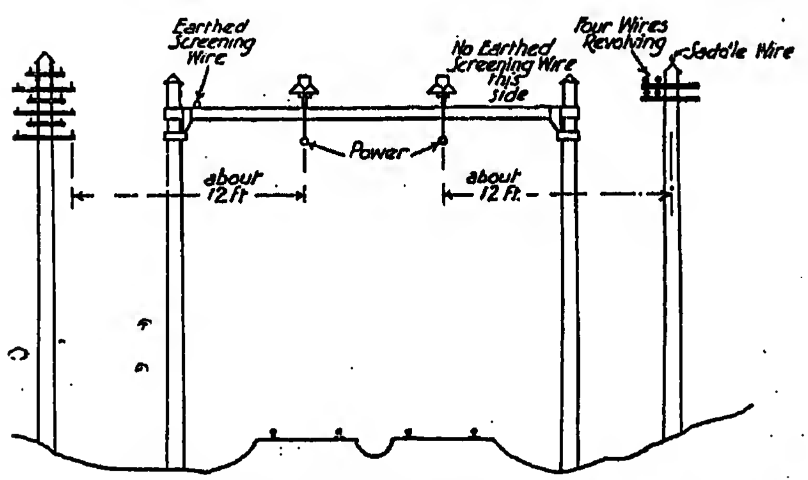


FIG. 33.—Showing relative positions of experimental lines and contact wires.

considerable reduction of the electrostatic potential. By comparison it was proved that the wire shown in the saddle position on the right-hand side of the figure, that is, on the side not provided with an earthed screening wire, was 320 volts, whilst the wire on the ridge of the screen side and of the same length as the other wire was charged to 48 volts only, a reduction of about 85 per cent. At the time these tests were taken, the saddle wire was the only one in position on the unscreened side. The tests were taken with a multicellular voltmeter and were roughly checked with a current measurement of the charge by earthing at one point through a high resistance, a thermo-milliammeter being used for the current measurement. These tests were taken with no trains running.

To ascertain more definitely the screening action of one or more wires on the same poles, No. 1 wire (shown in Fig. 33) was earthed at one point through a thermo-milliammeter, and the other wires were systematically earthed or disconnected as shown in the following table, in which are also shown the current readings with the varying conditions:—

TABLE 4.

Milli-amperes observed in No. 1	Conditions of other wires			
	Saddle wire	No. 2	No. 3	No. 4
26·1	Dis.	Dis.	Dis.	Dis.
21·9	Earthed	Dis.	Dis.	Dis.
18·6	Dis.	Earthed	Dis.	Dis.
18·9	Dis.	Dis.	Earthed	Dis.
18·6	Dis.	Dis.	Dis.	Earthed
15·3	Earthed	Earthed	Dis.	Dis.
12·3	Earthed	Earthed	Earthed	Dis.
9·9	Earthed	Earthed	Earthed	Earthed

The current strength will depend upon the resistance of the connection to earth. With similar conditions the charging current will be $I = 2\pi fCV$, where f = fre-

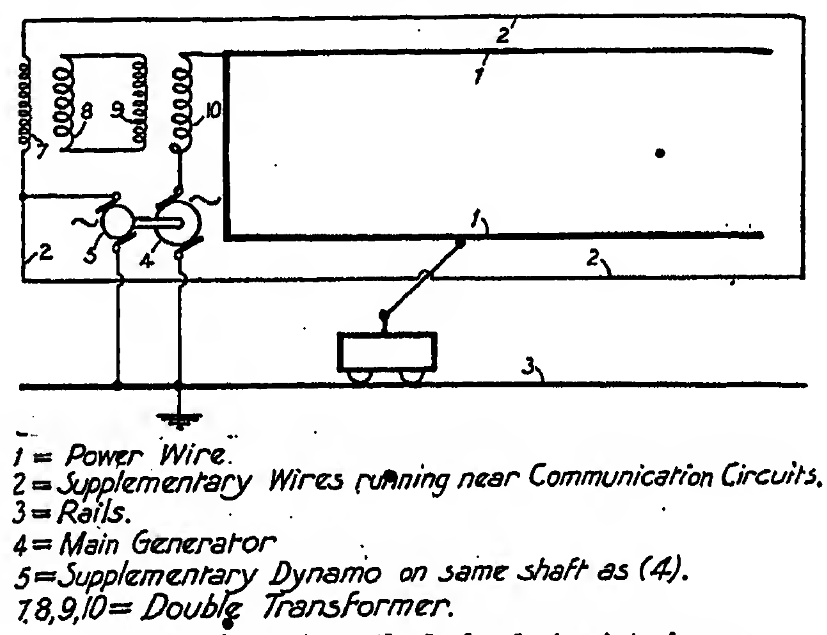


FIG. 34.—Sayers's method of reducing interference.

quency, C = capacity of communication circuit to earth, and V = charging pressure in the wire.

It may be of interest here to refer to a method, patented by Mr. Sayers* of the L.M. and S. Railway Company, for eliminating or reducing electrostatic and electromagnetic induction between contact wires and electric traction systems and adjacent communication circuits. Fig. 34 is a reproduction of the drawing in the patent specification. The method is briefly as follows:—Two special wires run in proximity to the wires interfered with where they are parallel to the railway. The special wires are charged from a dynamo which is running off the same shaft as the generator supplying the contact wires. The effect produced by this dynamo in the special wires counteracts the electrostatic disturbance produced by the trolley wires on the neighbouring circuits, as the two effects are 180° out of

* Patent No. 15 158/1909.

phase. In addition, the trolley wire is taken through a double transformer, of which the special wires form one of the windings. This arrangement is for counteracting the electromagnetic effect produced by the contact wire, as the currents in the contact and special wires will be similarly 180° out of phase. The author understands that this system was not actually brought into use.

Mr. Sayers also devised another method for reducing interference, and this was quite successful when tried

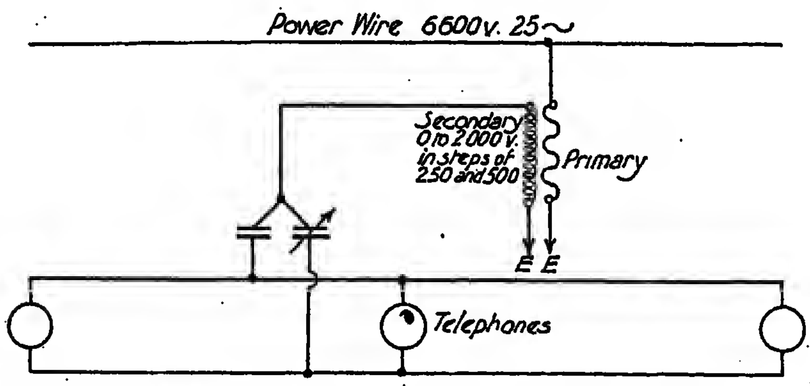


FIG. 35.—Sayers's method of reducing noise in telephone circuits.

experimentally by him. This is illustrated in Fig. 35. It will be seen that the telephone wires are electrically connected through condensers to the secondary of the transformer, the primary of which carries the power-circuit current. One of the condensers is variable.

The Brighton section of the Southern Railway is of interest in that a serious attempt has been made in the lay-out to prevent leakage and electromagnetic induction, and, although complete success has not been attained, the steps taken have undoubtedly minimized considerably the injurious effects likely to arise from those causes. The contact wires are sectionalized and are fed from feeder or distribution cables laid alongside the track. This reduces the electromagnetic disturbance to some extent, compared with the simple lay-out, as the current being fed into the trolley wire from opposite directions tends to neutralize the effects on neighbouring circuits. The principal steps have, however, been taken with the return of the currents, two conductors being employed to assist the return, apart from the rails and earth. One of the return conductors—the "distributor outer"—is connected to the rails by a copper bond. In the original installation between London Bridge and Victoria, each rail was connected to this distributor outer, but on the subsequent extension this has been modified, the rails being bonded together and connected to the distributor outer at intervals. The other return conductor, called a "booster" cable, is connected to the distributor outer, and thus to the rails, at a few points only. Both these cables run beside the track, and if the whole of the current returned in them it would have a considerable effect in counteracting the electromagnetic induction from the contact wires and the distributor. The action of the booster cable is as follows:—

At most of the feeding points a portion of the current is taken through a 1 to 1 transformer, to the secondary of which is connected the booster cable. The effect of this arrangement is to suck back the current through the booster cable, the E.M.F. produced by the transformer on the rails opposing any current returning in the rails. This action is illustrated in Fig. 36. Sir Philip Dawson has stated * that the distributor outer and the booster cable accounted for the whole of the return current between them, tests showing that with the booster cut out the distributor outer carried 84 per cent of the current and the booster 16 per cent. With the booster in operation, however, the booster cable carried back 100 per cent.

In spite of this arrangement, however, a considerable amount of trouble occurred with the opening of the section to the Crystal Palace and Tulse Hill. Many police and fire-alarm circuits were interfered with, and some public telegraph circuits. The operation of the latter was improved by the use of resonant shunts of the type already described. The faults caused on the police and fire-alarm circuits were sporadic and it was considered best to divert these and the police circuits from the track. The noise produced in the few telephone circuits concerned was not great—certainly not so disturbing as that experienced on circuits near the Lancaster–Heysham line. It should be observed, however, that the majority of the circuits affected were only exposed for short sections of route. A number of tests were made which showed that the electrostatic effects were inconsiderable. This is probably due to the earthed structures carrying the contact wires and to the numerous earthed telegraph wires on the routes. The electromagnetic effects could not, however, be ignored. On a telegraph line running parallel to the track for about 6 miles, with a separating distance

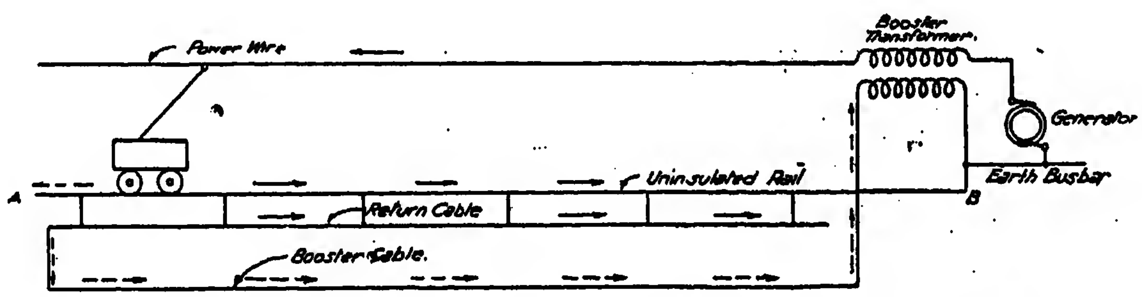


FIG. 36.—Booster and booster cables—Southern Railway (Brighton section).

The booster transformer produces between A and B an E.M.F. opposing that of current returning in the rail, return cable and earth, whilst providing an alternative low-resistance path through the booster cable.

—> Path for power circuit and return without booster.
- - -> Return current with booster.

* *Minutes of Proceedings of the Institution of Civil Engineers*, 1911, vol. 186, p. 1.

varying between 20 and 90 ft., 30 volts (R.M.S.) was induced.

There are no high-speed telegraph circuits on the railway as at present electrified, but tests with high-speed transmission showed that satisfactory working would not be possible on this particular line. Perfect signals could be transmitted, with the railway not working, at 200 words per minute. With an induced voltage of 20 these signals were unreadable. Even with lower speeds, such as 40 words per minute, an induced voltage of 11 mutilated the signals.

There are other methods of producing better balance on this type of railway which are variations of that employed on the Southern Railway (Brighton section). Figs. 37, 38 and 39 indicate the application. The method can be followed from the figures, the object being in all cases to reduce by means of boosters the current straying from the rails, with the addition in the last two cases of line connections which tend to neutralize further the effects of the current in the contact wire by providing return overhead conductors.

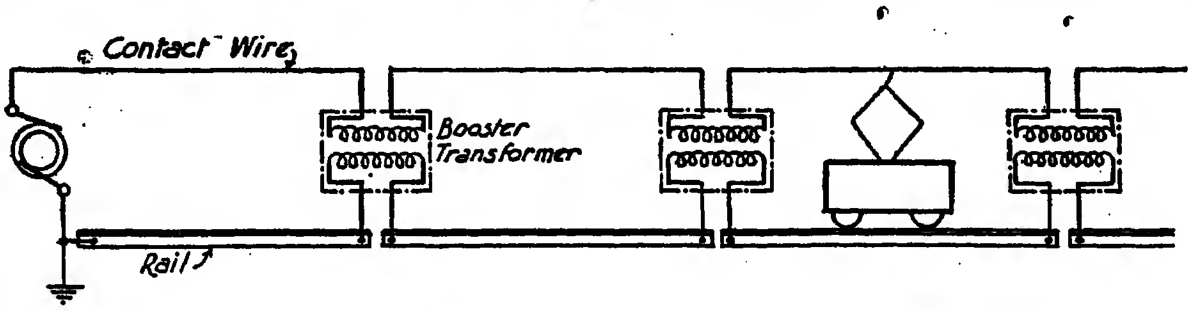


FIG. 37.—Booster transformer—direct in rails.

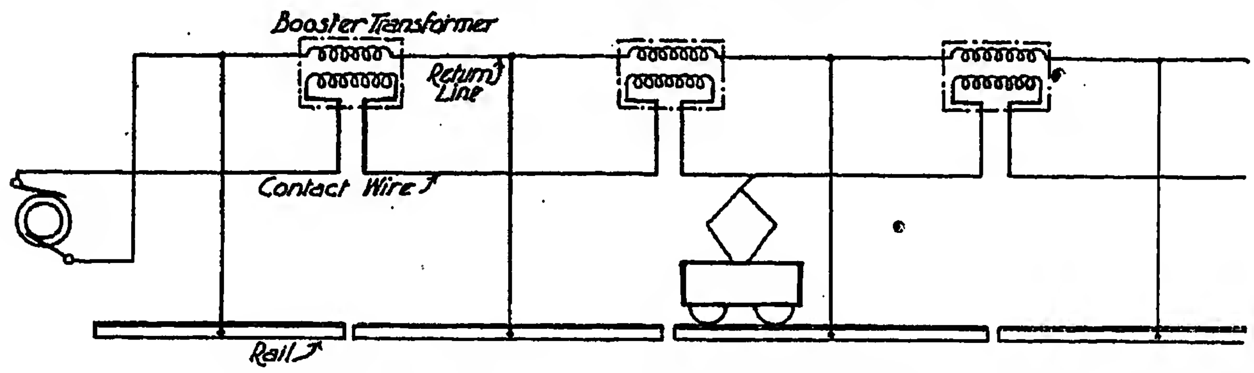


FIG. 38.—Booster transformer with supplementary return.

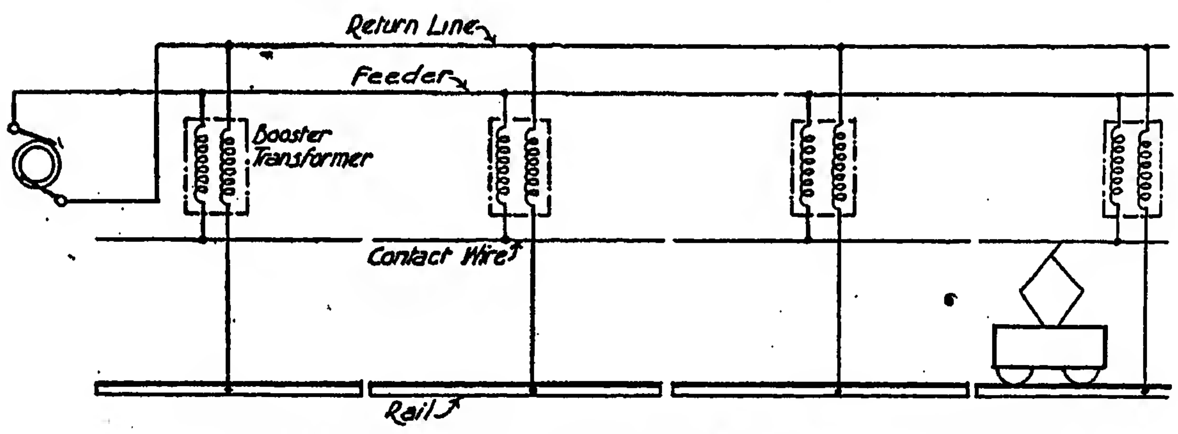


FIG. 39.—Booster transformer with supplementary return and feeder.

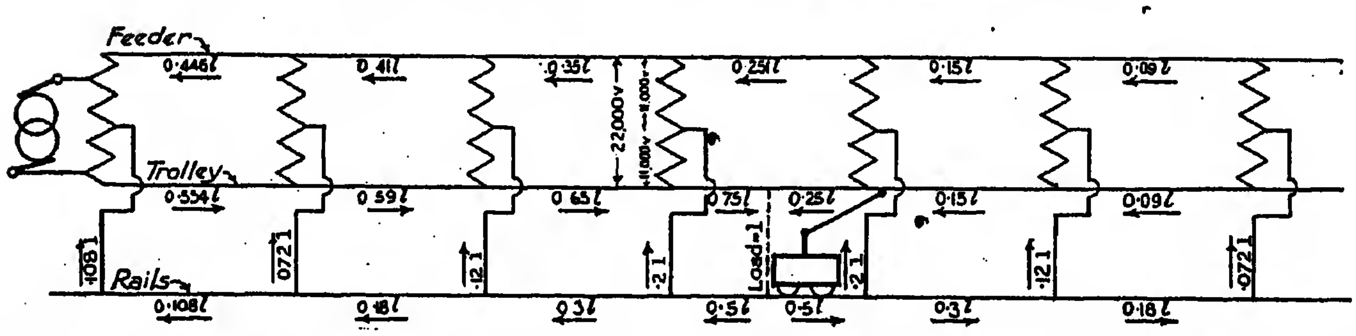


FIG. 40.—Lay-out of New York–New Haven Railway. Single-phase railway electrification: auto-transformer distribution system.

The New York, New Haven and Hartford Railway adopted a different method of working in the early part of 1914, the general lay-out being shown in Fig. 40. A 25-frequency current is delivered from the power station at 22 000 volts. One terminal of the 22 000-volt

transformers is connected to four feeders, two on each side of the track. The other terminal of the 22 000-volt transformer is connected to the trolley wires in multiple, the middle point of the 22 000-volt transformer being connected to the rails. There is thus 11 000 volts between the trolley wires and rails, 11 000 volts between the feeders and rails, and 22 000 volts between the trolleys and feeders. At intervals of about 2 miles west of the power station, and at greater intervals east of the power station, there are connected between the trolleys and feeders 2 000-kVA auto-transformers having the middle point connected to the rails. These transformers are for the purpose of balancing the load on the system. With this scheme of distribution, assuming a train to be located in a section between two auto-transformers, the current delivered to the locomotive from the trolleys would flow along the rails in opposite directions from the locomotive, the division of current east and west depending upon the location of the train, and portions of the current would be delivered back to the overhead wires by the auto-transformers on either side of the location of the locomotive in about the following ratio:

Assuming that the current flowing in the rails in one direction from the locomotive is unity, 40 per cent would be delivered to the overhead system by the nearest auto-transformer; 40 per cent of the remainder, i.e. 24 per cent of the total, by the second, and 40 per cent of the remainder by the third, and so on. This scheme tends to minimize disturbances upon paralleling telephone and telegraph lines, for the following reasons:—

(1) Excepting where the load is near the end of the line or near the power house, the unbalanced currents in the rail and earth flow in opposite directions from the location of the locomotive and in about equal amounts; and
(2) The distance over which the track currents flow is greatly reduced.

It is stated that this method has been of much benefit in reducing stray currents and has effected improvements in the inductive problem connected with this railway.

The author is, perhaps naturally, prejudiced against a system of electric traction which is likely to have such deleterious effects on communication circuits, but he is not without hope that a satisfactory solution of the problem will be found. It has apparently not been found so far, as a recent communication in the *Teknisk Tidskrift* (vol. 53, pages 45–51) by A. Holmgren, states that the shifting of the telephone lines from the Stockholm–Gothenburg railway will cost 68 million kronor (say £400 000) for the ordinary lines, and 17 million kronor (£100 000) for the railway communication lines. This fact is significant, following, as it does, an inquiry by the Swedish Government into the matter.

Electric light and power systems.—Electric light and power systems in this country are classified according to voltage employed under four headings:

Low pressure: up to 250 volts.
Medium pressure: 250 volts to 650 volts.
High pressure: 650 volts to 3 000 volts.
Extra-high pressure: above 3,000 volts.

It has not been usual to employ direct current at higher pressures than 500 volts on electric light and power circuits. Distribution of energy in the great majority of cases is by means of underground plant, but there has been a considerable increase in the number of overhead lines in recent years.

Leakage.—Electric light and power systems are not allowed to have more than one earth connection on each distinct circuit, with certain few exceptions, and this restriction has an important bearing in preventing interference by leakage currents. The Regulations of the Electricity Commissioners lay down that the insulation of a power system shall be such that not more than 1/1 000th part of the maximum supply current returns via the earth connection.

Interference by leakage currents occasionally occurs as the result of faults on low- and medium-pressure power systems, but they are not common. Faulty insulation on a power system may not in itself actually result in leakage currents affecting telegraphs or telephone circuits, but may produce inductive disturbance owing to the unbalancing of the currents in the different conductors of the power system. An example of this type of case was that which occurred many years ago when practically the whole of the telegraph service to the Continent was stopped owing to the use of the earth as a return on the 10 000-volt single-phase system between the West End of London and Deptford. The power-cable route followed the South-Eastern Railway, on which were also the Continental telegraph circuits, and it was the inductive effects which interrupted the service. The interruption was reported in the Press at the time as having been due to "an electric storm."

Induction.—So far as inductive effects are concerned, the great majority of electric light and power systems used generally for distribution purposes do not materially affect communication circuits. Only metallic circuits are allowed, and the use of underground cables predominates. Where underground power mains cause trouble, it is usually associated with the employment of a generator having a bad wave-shape on a three-phase system with the neutral point earthed. In other cases, trouble may arise from faults. For instance, the outer of a concentric cable carrying single-phase current may develop an earth, and this may result in different values of current in the inner and outer conductors owing to the leakage, as concentric cables are usually definitely earthed at the feeding point. Cases of interference with overhead telephone circuits have occurred from both these causes. The author has had experience with one rather severe case of interference from an underground three-phase line affecting an overhead trunk line running parallel to it for about 3 miles, some features of which are perhaps worth mentioning. The system was a 6 000-volt one with the generator earthed at the neutral point and feeding direct into the cables, which were of the usual type, armoured, lead covered and laid direct in the ground, except for certain sections where the cable was placed in troughing filled in solid with bitumen. The inductive effect was found to be entirely due to the charging current produced by the third harmonic and its multiples. The noise in the trunk circuits disappeared with the removal of the

earth connection. A curious result was noticed when listening with a search coil on the cable route. Whilst a very pronounced note was picked up at all points where the cable was laid direct in the ground, at places where the cable was laid in the bitumen, and in the station where the cable sheathing was isolated from earth, hardly any noise could be heard. This effect was no doubt due to the whole of the earth capacity current being in the sheathing at these latter points and so neutralizing the effect of the capacity current in the cores. In passing, it should be remarked that the trouble was cured in the first instance by removing the earth from the alternators and providing an alternative earth at a transformer in the generating station. Later, a very high resistance (paper layers) was substituted for the direct earth connection at the generators, with satisfactory results.

As might be anticipated, overhead power lines are more likely to produce interference than those underground, and serious cases are confined to high-pressure and extra-high-pressure systems. The fact that overhead power-transmission systems follow cross-country routes has no doubt been a saving factor in this country, as there is much less chance of communication lines running parallel with power lines for any appreciable distance.

Standard practice with power transmission is to employ a three-phase 3-wire system. With pressures up to 11 000 volts, generators feed directly into the overhead lines. Above that pressure, step-up transformers are employed. Fig. 41 illustrates various arrangements that may be made :—

(*a*) Generator to line.
(*b*) Transformers delta-delta.
(*c*) Transformers delta-star.
(*d*) Transformers star-delta.
(*e*) Transformers star-star.

The method employed for connections has a very important bearing on the possibility of producing interference owing to the development of the third harmonic or multiples thereof.

In the case of star-connected three-phase systems with the neutral point earthed, the third harmonic in each of the conductors is in phase and this causes an alternating voltage to appear between conductors and earth of a frequency three times that of the fundamental. With only one earth on the system, i.e. at the neutral point of the star winding, the three wires are raised or lowered in voltage simultaneously in respect to the earth, and the effect on neighbouring communication circuits is wholly electrostatic and, generally, telephone circuits only are affected. If the power system is extensive, however, and other conditions are favourable, telegraph circuits may also be interfered with, as the charging current may be of considerable magnitude. If there be a second earth on such a system, a single-phase current will circulate between the two points over the three conductors in parallel, with the earth as return. This arrangement may be particularly undesirable from the point of view of interference.

(*a*) Generators supplying three-phase current and having the neutral point earthed are very prone to produce third harmonics and multiples thereof, and if such a generator be connected directly to an overhead line inductive troubles may be experienced on neighbouring communication circuits. The removal of the earth connection will remove the inductive interference. Modern practice, however, appears to be definitely in favour of working with an earthed neutral and as, in addition, an earth may be required in connection with the operation of protective gear on the power system, this course is usually objectionable and alternatives have to be found, if possible. Machines vary considerably in this matter of producing third harmonics, and it is frequently found that where several alternators are in use at a generating station, there is usually one which either is innocuous in this respect or produces very much less inductive interference; and if the earthing is arranged to be made at that particular machine, interference effects are removed altogether or made inappreciable. In other cases it may be found to have satisfactory results if the earthing be done at the neutral point on a step-down transformer instead of at the neutral point on the generator. Fig. 42 illustrates the arrangement. A transformer with a delta on the secondary side is the most effective, or, alternatively, a zig-zag star-connected transformer would probably be equally effective. The rating of such a transformer would no doubt have to bear some relationship to the capacity of the system and to the characteristics of the protective gear employed. The author has no information as to this. A simpler solution is the employment of a paper resistance in the earth connection. This provides what is practically an isolated neutral during normal conditions, and can be arranged to break down and provide a direct earth on the occurrence of a fault.

Where a generator has the neutral point earthed and supplies power to an overhead line through transformers, the type of connection of the transformers is of great importance from the point of view of inductive interference. The following briefly analyses the position (see Fig. 41).

(*b*) Delta-delta. There is no inductive interference from the third harmonic or its multiples. The third-harmonic magnetizing current circulates in both windings. There is a third-harmonic voltage in the windings but no third harmonic in the voltage or transmission line.

(*c*) Delta-star. The inductive interference effects are usually small. There is a third-harmonic magnetizing current in the primary winding only. A third-harmonic voltage appears between the lines and neutral on the line side and produces a third-harmonic current between the lines and earth.

(*d*) Star-delta. The inductive effects are only on the primary side. The third-harmonic magnetizing current circulates in the secondary winding only. The third-harmonic voltage appears between the line and neutral on the primary side. There is no third-harmonic voltage or current in the transmission line.

(*e*) Star-star. This is the worst condition for inductive interference. There is no third-harmonic magnetizing current. A third-harmonic voltage appears between the lines and neutral on both primary and

secondary sides, and the third harmonic current flows between the lines and earth if the neutral is earthed.

It will be seen that (b), delta-delta, is the best arrangement, and (e), star-star, the worst. A tertiary winding in the latter case will reduce the inductive effects.

The usual arrangement in this country is delta-star with the neutral point earthed.

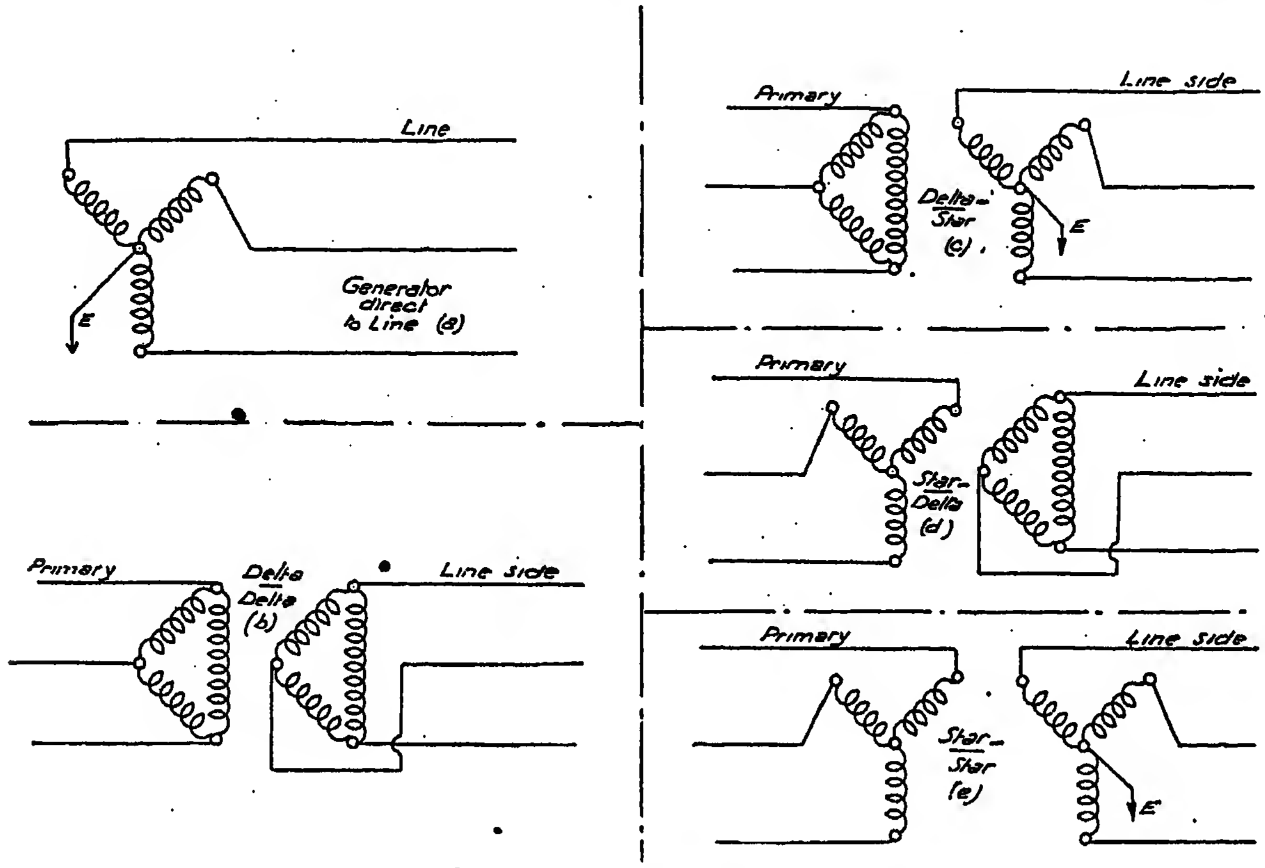


Fig. 41.—Generator and various transformer connections.

Interference from balanced voltages and currents on the power lines is not usual in this country. These effects depend upon the formation of the power lines, separation between the conductors and, as in all cases of interference, the distance between the power line and the communication circuit. It can be taken that the greater the spacing of the power conductors, the greater will be the magnitude of the inductive effects from these causes. Power wires have, however, to be given ample spacing in order to avoid short-circuits from wind, birds, etc. The avoidance of short-circuits is of importance from an interference point of view, as well as from the operating standpoint, as transient disturbances of a serious character may be caused by them. The power wires on supports either form an equilateral triangle, are horizontally in the same plane, or are arranged vertically one above the other. The last is the best arrangement, taking into account the effects of balanced voltages and currents. As pointed out in the relevant section, interference from balanced voltages and currents can be overcome by transposition of the power wires in the exposed section, so that each power wire occupies each of the conductor positions for equal distances in relationship to the communication circuits.

Multiple earthing on power systems.—Power systems may be connected with earth in accordance with Regulations made by the Electricity Commissioners for securing the safety of the public and ensuring a sufficient supply of electricity. Earth connections made for other purposes may be approved by the Electricity Commissioners subject to the concurrence of the Postmaster-General. The general practice in this country has been to allow only one earth connection on each distinct circuit. There have been exceptions; for instance, in the case of the constant-current series system of the Metropolitan Electric Supply Co., where an earth return on sections between substations is permitted in the event of repairs being required. It will be remembered that on this system the direct current is maintained constant at 100 amperes, the voltage varying with the load. The Electricity Commissioners' earthing approval stipulates generally that the earth connection shall be made at a neutral point on the system, the exception being in the case of a single-phase supply with a concentric cable having the outer earthed. The limitation of one earth connection is made primarily in the interests of the owners of communication circuits

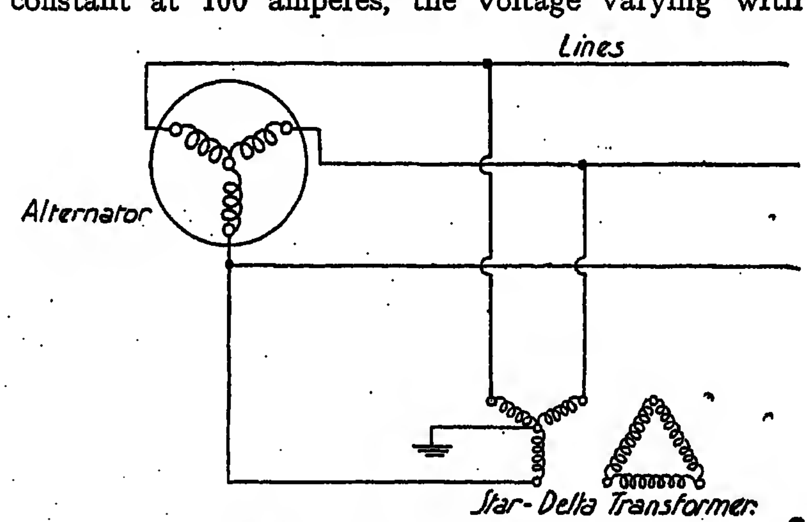


Fig. 42.—Earthing transformer.

(Post Office, railways, etc.) whose services might otherwise be injuriously affected. As pointed out earlier, interference may be produced by the residual voltages and currents with one connection only on a three-phase system; and, theoretically, two connections on such systems have always been considered to be particularly undesirable, as charging currents in such circumstances become circulating currents through the two earth connections. Practical experience has confirmed this in many cases, as the earthing of power circuits at more than one point has caused serious interference, especially in those cases where three-phase generators with the neutral point earthed have been feeding directly into a system and a second earth has unwittingly been made at a transformer or auto-transformer in the network. In 1920 it was found that the telegraph circuits between Newcastle and Sweden could not be worked at speeds high enough to carry the traffic, and the laying of another submarine cable was being seriously considered. No reason could be assigned for the failure to attain the proper speed of working, and power circuit interference was suspected. With the co-operation of the power company the cause of the trouble was traced to a second earth connection having been inadvertently made permanent following a fault. The removal of this second earth resulted in the speed of working on the submarine cable being raised by 12 per cent, and with it the need for another submarine cable disappeared. A very large sum of money was involved, as, the author understands, an expenditure of over £100 000 would have been required for the provision of such a cable.

The great growth of the power systems of the North-East Coast has brought into prominence difficulties in connection with the operation of protective gear where there is interconnection of networks and only one earth connection. The continuance of faults on this system in some cases resulted in serious disturbance to telegraph and telephone circuits. In one instance a fire was started in a terminal hut by the induced voltages in the communication circuits. The power company pointed out that whilst the provision of more than one earth connection might increase the interference from normal working of the power system, it would certainly decrease the possibility of serious trouble arising out of momentary disturbances of larger magnitude, and would reduce the risk of these latter continuing for any appreciable time. It was agreed that it would not be wise to have more than one earth on a circuit directly connected with a generator the neutral point of which was earthed, but it was contended that with delta-star

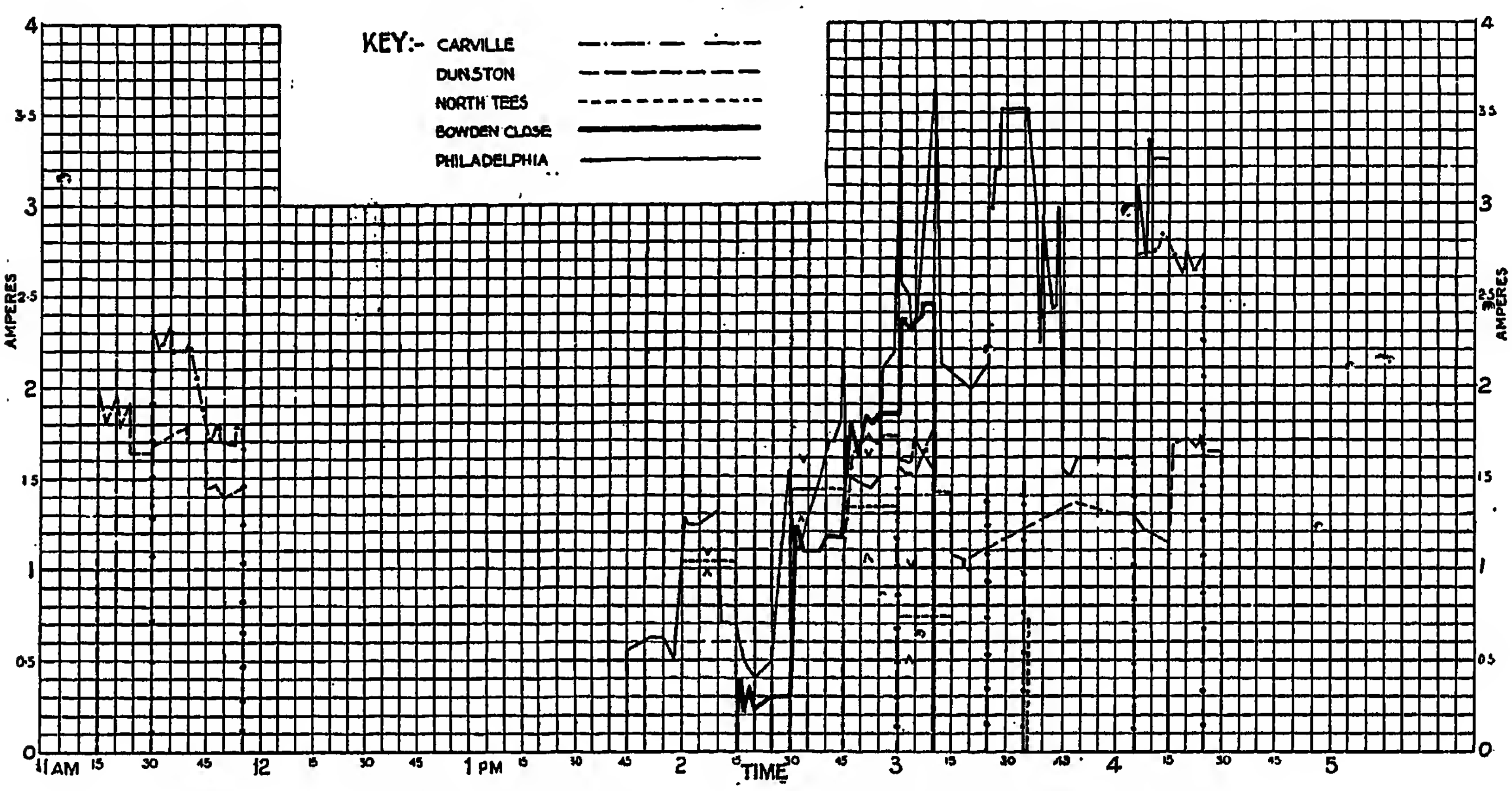


FIG. 43.—Neutral current on a 20 000-volt network; 11th May, 1922.

SCHEDULE OF TESTS.

Time	Neutral earthed at	Time	Neutral earthed at
11 a.m.	Philadelphia (instrument damaged).	2.45 p.m.	Philadelphia, North Tees, Bowden Close, Dunston.
11.15	Philadelphia, Dunston.	3.0	Philadelphia, North Tees, Bowden Close, Dunston, Carville.
11.30	Philadelphia, Dunston, Carville.	3.15	Philadelphia, Dunston, North Tees.
11.45	Philadelphia, Dunston, Carville.	3.25	Philadelphia, Dunston, North Tees, Carville.
1.45 p.m.	Philadelphia.	3.35	Philadelphia, Dunston.
2.0	Philadelphia, North Tees.	3.45	Philadelphia, Dunston.
2.15	Philadelphia, Bowden Close.	4.5	Philadelphia, Dunston, Carville.
2.30	Philadelphia, North Tees, Bowden Close.	4.15	Dunston, Carville.

In the tests at 11.15 and 11.30, Philadelphia was solid to earth. At 11.45 Philadelphia earthed through the resistance. In all the other tests in which Philadelphia enters, the earth is through a resistance. At 3.15 and 3.25 North Tees should have been clear but was not, and no readings were taken there over this period.

Vertical lines having no curve continuation mean that places were earthed but no readings were taken. Small barbs above and below the North Tees curve represent maximum and minimum readings.

transformers feeding a system, the triple-frequency currents would be small and would not be likely to increase to any extent the normal interference. Sir John Snell suggested that the matter should be put to the test by co-operation between the Post Office and the companies concerned, and a series of observations was arranged to be made with various conditions. The currents in the earth connections were measured with the different combinations, and arrangements were made to note the effects on telegraph circuits with various types of apparatus, and also on telephone circuits.

The currents in the earth connections at the various points are shown diagrammatically in Fig. 43. It will be noticed that the 0·6 ampere on one earth connection increased to 3·6 amperes with all the earths in use.

The telegraph circuits under observation were not affected, and although there was an increase in telephone interference this was inappreciable. It should be pointed out, however, that the routes of the communication circuits under observation were not very favourable for interference. As the result of these tests, multiple earthing on the North-East Coast systems has been agreed to, subject to certain qualifications, which include an embargo on generators feeding directly into a circuit. The matter of interconnection of this latter type of system was dealt with in a paper* on "The Parallel Operation of Electric Power Stations," read by J. S. Peck before the Institution.

Transient effects from abnormal conditions.—The earthing of power lines by means of a Petersen coil has found favour in some countries. The purpose of the coil, which is a reactor, is to limit the severity of accidental faults which might otherwise interrupt service or endanger equipment. In this method, the neutral of the system is earthed through an inductance which is in resonance at the fundamental frequency with the total direct capacity of the system to earth. The arrangement has the effect of suppressing arcing faults to earth, tending to extinguish the arc and prevent it from re-striking. The effect of this on the interference problem was not apparently mentioned in Petersen's original description in the *Elektrotechnische Zeitschrift* of the 2nd and 9th January, 1919, but it is clear that, if effective, it will reduce the chances of inductive interference during abnormal conditions on a power system. The effect of the reactor in modifying the conditions as regards inductive interference during normal operations has been analysed by H. M. Trueblood in an important article in the *Bell System Technical Journal*, July 1922. For the reduction of the effects of triple-frequency residual currents and voltages, the reactor appears to be preferable to earthing through a resistance, but, on the other hand, it will accentuate the effects of fundamental frequency if the power-line is unbalanced. It is possible, however, that the Petersen coil will not combine with any of the standard protective systems.

A paper by S. Kudo and S. Bekku in the *Journal* of the Japanese Institution, May 1923, deals with the placing of a high resistance in the neutral earth connection, and states that this suppresses normal interference, but it is not known whether transient effects are reduced.

* *Journal I.E.E.*, 1917, vol. 55, p. 61.

Conclusions.

It will no doubt be agreed that the problem of inductive interference is not simple, and, although the troubles cannot be said to be serious in this country, one can foresee that they may become so if due consideration is not given to the possibilities. Many interests are concerned and the author would place responsibility for solving the problems in the following order:—

First, the designer, who by producing machines free from harmonics can practically eliminate the whole trouble with telephone circuits.

Secondly, the power engineer, who can plan his system to be balanced as regards loads and lines, employ transformers with connections least likely to cause trouble and worked at a low magnetic density, and by proper precautions and maintenance reduce faults on his circuits.

Thirdly, the telephone engineer, who, by designing his circuits and apparatus in such a way as to reduce the possibilities of out-of-balance and by the proper maintenance of his lines, can do much to avoid interference.

Fourthly, the protective-gear engineer, who, last but not least, will prevent those breakdowns which result in very serious trouble due to abnormal happenings in the power system. These may be transients but he must endeavour to make them micro-transients.

It is perhaps impossible to produce rotating electric machines free from harmonics, and similarly it must be expected that there will be some distortion of wave-form in power transformers owing to the employment of iron in the magnetic circuit, but the author suggests that if those responsible are made aware of the significance of these features in connection with the interference problem, they will be kept within reasonable limits.

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APPENDIX.

METHOD OF GETTING RID OF TELEPHONE INTERFERENCE FROM A MERCURY-ARC RECTIFIER.

By Professor E. W. MARCHANT, Member.

A method has been devised by which the voltage ripple found in some types of converting machinery can be almost entirely got rid of. The particular case dealt with was a mercury-arc rectifier, and the oscillograph record of the voltage wave is shown in Fig. 44. The

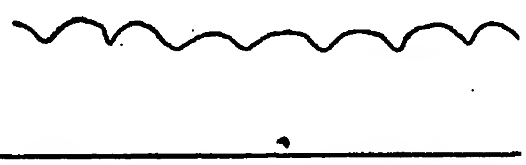


FIG. 44.—Rectifier d.c. voltage: 470 V.

voltage variation amounted to $\pm 9 \cdot 5$ per cent of the average steady P.D., and when current was supplied for lighting purposes from the circuit it gave rise to considerable disturbance in neighbouring telephone lines. An analysis of the voltage showed that it consisted of a ripple of about 300-cycle frequency, but that there was also present a component of 600 cycles. The analysis also showed that the higher harmonics of the voltage wave were relatively small. The actual figures obtained in the analysis of the first, second, third, fourth and fifth harmonics were as follows:—(1) 9·5 per cent; (2) 2·5 per cent; (3) 0·8 per cent; (4) 0·83 per cent; and (5) 0·42 per cent. It was thought that if the first two ripples could be eliminated, the remaining higher-frequency harmonics would not cause any serious trouble, and this actually proved to be the case.

A method which suggests itself for a single-phase rectifier is to use a shunt consisting of an inductance and capacity in series, and to adjust the inductances and capacities to be of zero reactance for the ripple frequency and so practically to short-circuit the rectifier for currents of ripple frequency. Instead of applying such a circuit to each arc circuit of the rectifier, it was decided to use a single circuit, tuned to the frequency of the resultant ripple of which the analysis is given. This arrangement (Fig. 45) was found to be quite successful in dealing with the "6 arc" circuit, the ripple current through the shunt distributing itself along the different arc circuits in succession. If, however, this shunt circuit is used alone, a relatively large current of several hundred amperes will pass through it and through the different arcs, and the reduction in voltage variation will not be very marked.

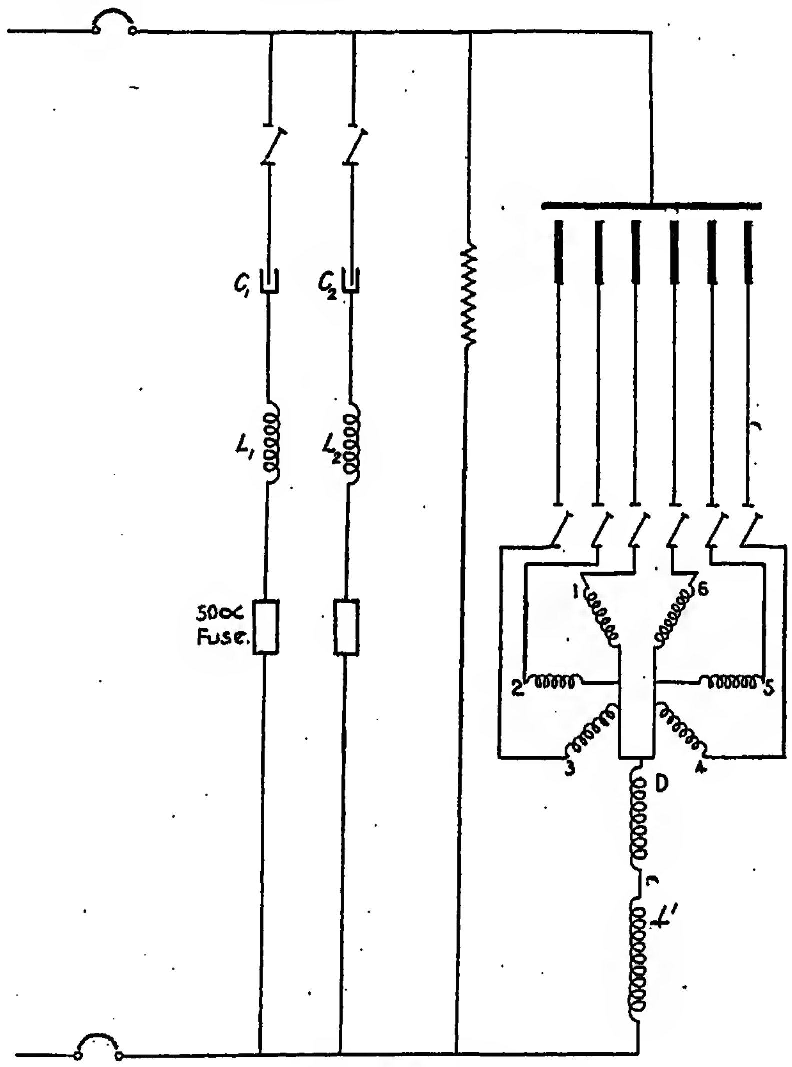


FIG. 45.—Diagram of circuit.

In order to limit the current, an additional single inductance coil L′ is placed in the main circuit of the rectifier, the currents through the various branches of the rectifier combining to flow through this inductance and being reduced to as small values as may be considered necessary. The effective impedance of the shunt, for the ripple which it is desired to get rid of, is equal to its effective resistance only. The value of the effective resistance, however, is not simply the ohmic resistance, but includes the effective resistance due to iron loss in the choking coil (if iron is used) and also the effective resistance due to the dielectric loss in the condenser. This latter, however, is as a rule very small. The R.M.S. current, i, flowing through the shunt is determined by the magnitude of the voltage ripple and is equal to $v\sqrt{/[R^2 + (L'\omega)^2]}$, where v is the R.M.S. value of the voltage ripple, R is the effective resistance of the limiting inductance and the shunt, L' is

the value of the limiting inductance and $\omega = 2\pi \times$ (frequency of ripple). The voltage across the shunt when this current is passing is equal to iR, and the ratio of the voltage ripple before and after introducing this arrangement is, therefore, given by $\sqrt{[R^2 + (L'\omega)^2]}/R$. By increasing the value of L' in comparison with R, it is therefore possible to reduce the voltage ripple on the main supply to negligible dimensions. In designing the shunt circuit the consideration which is of most importance is the maximum voltage which will be produced on the condenser; approximately this equals $i/C\omega$ and, therefore, if the voltage is to be reduced, the value of the capacity used must be increased. At the same time, the value of $L_1\omega$ must be kept equal to $i/C_1\omega$, where $\omega = 2\pi \times$ (frequency of the ripple). The condenser C_1 of course prevents any direct current passing through the shunt circuit, and the current flowing through the shunt due to ripples other than that for which the inductance and capacity balance, is relatively small.

Owing to the high frequency of the ripple current, it is advisable to use an air-core inductance at L_1, and in some cases stranded wire, in order to reduce eddy currents in the windings. In the actual shunts used, the power condenser was insulated for 600 volts (maximum). It was decided to design the shunt so as to reduce the voltage variation from $\pm$ 44 volts to $\pm$ 1 volt. The shunt was designed to carry a current of 10 amperes. The R.M.S. value of the voltage ripple was about 31 volts and the reactance of the limiting inductance ($L'\omega$) was approximately 3 ohms. The iron-cored inductive coil L′ was made with approximately this reactance and was arranged as shown in the diagram. There is a steady voltage of 460 on the condenser and therefore only 140 is available for the ripple, if one is to keep within the safe working limit of the condenser. The value of the capacity used was 100 μF, which gave a voltage variation on the condenser of 53 volts (75 volts max.). A rather smaller capacity might have been used, but it was thought better to provide an ample margin of safety against breakdown, as the maximum voltage due to the ripple may be twice the normal maximum voltage (i.e. 150 volts) at the instant at which the condenser is switched on. The power factor of the condenser is 0·0016 and the effective resistance is therefore 0·0085 ohm. The value of the reactance

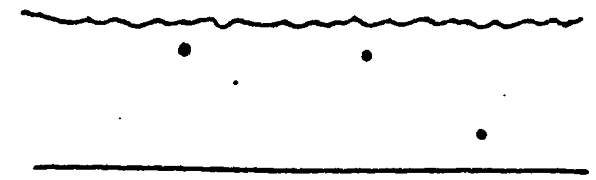


FIG. 46.—B rectifier voltage; 1st circuit connected.

$L_1\omega$ in the shunt was 5·3 ohms, ω being equal to 600 π. This gave $L_1 = 0{\cdot}00282$ henry. A similar shunt was designed for the second harmonic for which the frequency is 600 cycles per second, and the maximum amplitude of the voltage was 11·5 volts. In this case a capacity of 50 μF was used and an inductance of 0·00141 henry. The current flowing through this shunt was estimated to be about 2 amperes, and the resistance corresponding to this current, in order to reduce the voltage variation to 1 volt, would therefore be about

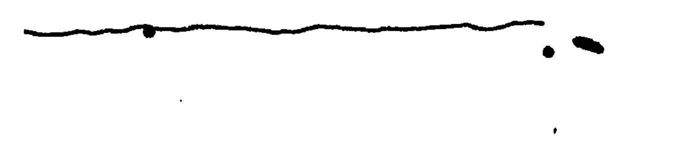


FIG. 47.—C rectifier voltage; two circuits connected; no load except auxiliary resistance.

0·5 ohm. The shunts were adjusted by experiment before being installed, but, when being fitted, a coil connected to a valve amplifier was hung near the busbars and the shunts were adjusted until the noise heard in the telephone connected to the amplifier was a minimum. The effect of using these shunts is shown in Figs. 46 and 47. It will be seen that the ripple is very much reduced by using the first shunt only, and when both shunts are connected the voltage ripple shown on the curve (Fig. 47) is almost negligible.

DISCUSSION BEFORE THE INSTITUTION, 10 APRIL, 1924.

Mr. A. J. Stubbs: We probably all recognize that the path of progress is to be looked for most advantageously in the way of co-operation. Some problems are awaiting solution, and others, which we fail to recognize for want of co-operation, can only be solved in that way. One instance of the benefit of co-operation is the cable relay of S. G. Brown. I think it is right to say that that relay could not have been designed by a telegraph engineer as such, neither could it have been conceived by a power engineer as such. It is due to the adventitious combination of the two qualities in one individual that we own that very useful invention. I have found that power engineers are very interested in the illustration on page 839. Given a power circuit in close proximity to a theoretically perfect telephone circuit, when, in the ordinary course of business, that perfect telephone circuit is put through to another less perfect circuit, it may very well be that, although both the original telephone circuits are good and useful by themselves, in combination they may possibly become unworkable. It is reasonable to suggest that no power engineer in the course of his ordinary experience would imagine that such a result would occur. Again, it is difficult for the power engineer to realize the magnitude of the interests that are jeopardized by the minute details which the communications engineer has to press upon his notice. The conductors themselves are smaller than the difference between two adjacent sizes of conductors which the power engineer uses; but the author shows on page 854 that inadvertently allowing a temporary second earth to remain on the power circuit in the short distance between Newcastle and the English coast nearly involved the laying of a new submarine cable at a cost of over £100 000. The author includes in the bibliography Prof. Hughes's researches on induction, but does not mention his

name on pages 831 to 869, and this omission seems to give countenance to the idea that the cross-over system is American. It is not. When the application in practice of Hughes's researches was first introduced by Preece at the Post Office, the cross-over system was fully considered, but the fact that the sections of uniform routes in England were so short forced us to the conclusion that a complete transposition of the circuits at every fourth pole was best calculated to meet our requirements. I doubt whether, if it were possible to produce the plans of the cross-over system that I evolved by Preece's instructions at that time, there would be found to be any material difference between them and Fig. 19 of the paper.

Prof. E. W. Marchant: As the author says, the greater part of the trouble due to interference is caused by the higher harmonics which occur in power distribution systems. A frequency of 25 periods gives an unpleasant hum in a telephone, but does not seriously interfere with speech. Mr. Osborne gives the relative effects of current at 1 000 frequency and 25 frequency as 60 000 to 1. That seems to be a very big figure, and I should imagine that it would depend to a very considerable extent on the observer. I should be glad if the author would state whether any other figures are available in this connection. One matter which we have investigated to a considerable extent in Liverpool is referred to on page 841, viz. the presence of higher harmonics of current in the neutral return of a power distribution system. It is, of course, well known that, when there are a number of alternators in parallel (the neutrals being coupled together), unless the alternators are exactly similar to one another, very large currents, of three times the fundamental frequency, will flow between the neutrals. I do not think, however, that it is so generally known that if there is an earth on only one of the alternators, and these are connected to a three-phase cable network with earthed sheath, a very considerable current flows from the generators through the capacity between the lines and the sheath to earth, and so back to the generators. The currents that will flow from the conductors to the sheath will be of either three times or a multiple of three times the fundamental frequency. I do not think that these currents are likely to cause any very serious interference between power circuits and telephone circuits if suitable precautions are taken, but it is well to realize that these currents flow, even when only one alternator neutral is earthed, provided that the cable system is earthed also. They only flow between the earthed neutral point of the alternator and the earth of the cable system. It is, of course, comparatively easy to avoid harmonics in the voltage waves of alternators. An alternator which is designed to give a pure sine wave is certainly the best solution; but there are also other methods. The author says that he regards the earth connection as being an essential part of the telephone system. It seems to me that if main-line railways are electrified, the prevention of interference with telephone systems if there is an earth connection on the telephones will be a matter of very great difficulty. I should think that the best way of getting rid of interference would be to use metallic circuits only on telephone systems and to avoid earth circuits, except in certain special cases. I should like to refer to the method invented by Mr. Turney and myself for getting rid of harmonics. The reason I do so is that Fig. 9 in the paper is not quite correct. The object of the method described was to get rid of components in the pressure curve between the neutral point and any phase, which were three times, or a multiple of three times, the fundamental frequency. If there are such harmonics present in an alternator there is no component of the triple frequency or multiple of the triple-frequency component in the voltage between the lines. The pressures in the three phases due to the triple-frequency components are in phase, and therefore there is no triple-frequency component in the line pressure. The only place where the triple-frequency component has to be eliminated is between the line and the neutral. The essential feature of the method is a connection, such as is shown in Fig. A, of shunts

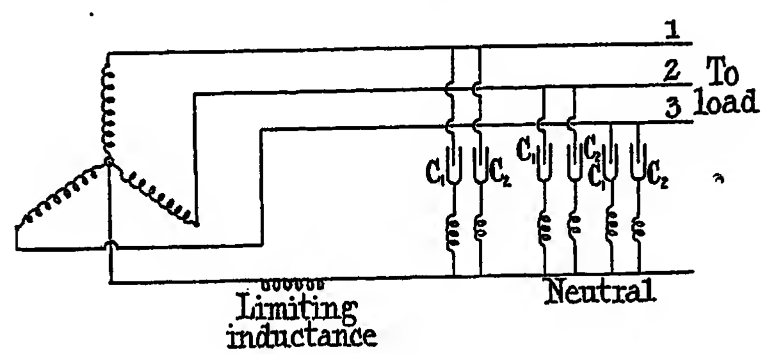


FIG. A.

between the lines and the neutral with a view to getting rid of the triple-frequency component between those two points. The double set of shunts, C_1 and C_2, shown in the figure can be used for getting rid of two of the high-frequency components of the pressure. The advantage of this arrangement is that a single limiting inductance can be used, which only carries the triple-frequency (or multiple of triple-frequency) shunt currents, and which, therefore, need not be of such large dimensions as if it were carrying the whole load current.

Mr. E. Parry: The author refers on page 835 to some theoretical investigations of my own into the phenomena of electrostatic and electromagnetic induction between power circuits and telegraph and telephone circuits. He also refers to some confirmatory experiments conducted by Messrs. Marsden and Caldwell. Those investigations were instituted with the object of establishing a method of predetermining the induction for any given combination of circuits and disposition of conductors, and the results went a long way towards achieving that object. Amongst other results it was discovered that no correction is necessary to bring the equations into harmony with facts, in the simple case of a single power circuit acting upon a well-insulated parallel conductor. Neither is any correction necessary on account of the proximity of other conductors, so long as they also are insulated. A considerable disparity was, however, disclosed between theory and experiment in the case of electrostatic induction between a 66 000-volt power circuit and a pair of telephone con-

ductors carried on the same poles and distant only 6 ft. 6 in. from the plane of the two lower conductors. The value of the impressed voltage was observed to be 1 730 volts, as compared with 3 565 volts calculated. The disparity is evidently due to the fact that the insulators supporting the telephone line were incapable of sustaining such a high voltage, and were draining the charge to earth. A much more interesting case than the one referred to, and one of more practical importance, is the case where a pair of three-phase 11 000-volt power circuits occupy one side of a road, and telegraph and telephone circuits occupy the other side. Such a combination is of frequent occurrence in other countries, though rather an exception in Great Britain, and the question arises how far the two services can be run in parallel under given conditions. I now submit a contribution to the solution of the problem, which may be of particular interest to some members of the Institution. The power circuits are three-phase and each circuit consists of 19/14 conductors triangularly spaced 2 ft. apart. The plane of the two lower conductors is 27 ft. 4 in. above the ground, and a distance of 5 ft. 4 in. separates the upper conductors of the two circuits. The telephone or telegraph wire acted upon is assumed to be No. 11 S.W.G. and the frequency is 50 cycles per second. The pressure between phases is 11 000 volts, and the current is assumed to be 100 amperes per phase. Fig. B shows the variation of the electrostatic induction with the distance measured from the centre line of the pole carrying the two power circuits to the vertical line through the telephone or telegraph wire, and the

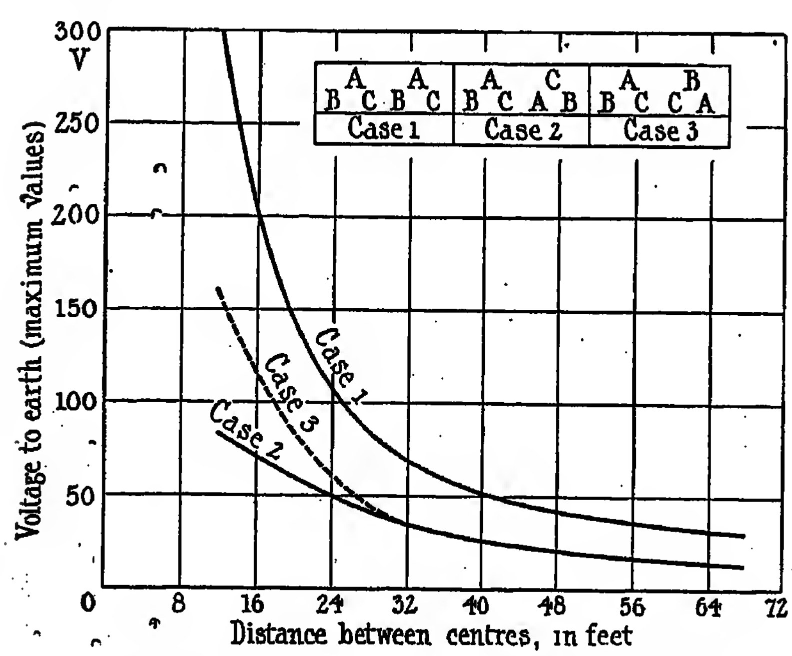


FIG. B.—Electrostatic induction between power and telephone circuits.

Power circuits: 19/14 at 2 ft. spacing, 11 000 volts, 50 periods, three-phase. Telephone circuit: No. 11 S.W.G.

impressed voltage is given for three conditions of phase. In the first case the two power circuits are symmetrical, in the second case the phase of one circuit is rotated in space through 120° with respect to the other circuits, and in the third case the phase of one circuit is rotated through 240° in respect to the other circuits. It will be seen from the figure that the lowest induced voltage is obtained under conditions specified in case 2 above, also that the induced voltage at a distance of about 66 ft. is of the order of 10 volts. Fig. C shows the electromagnetic induction in volts per mile at different distances between the circuits and for the three different conditions already specified in the case of the electrostatic induction. It will be noted that

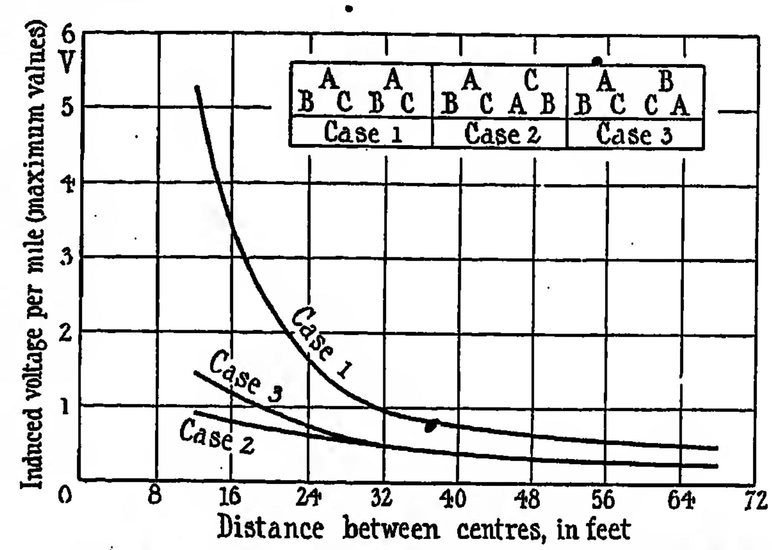


FIG. C.—Electromagnetic induction between power and telephone circuits (100 amperes, max. value, in each power circuit).

Power circuits: 19/14 at 2 ft. spacing. Telephone circuit: No. 11 S.W.G.

the curves for cases 2 and 3 merge at a distance of about 32 ft. and that the values of the induced voltage for distances in excess of 32 ft. are one-half that in case 1, the value in cases 2 and 3 at a distance of 66 ft. being 0·25 volt per mile per 100 amperes. The figures do not, of course, represent the whole of the circumstances, but they form a basis of discussion and of an arrangement between the two conflicting interests.

Mr. W. J. Thorrowgood: At the time when the City and South London Railway was first brought into operation the London and South-Western Railway had a telegraph circuit between Nine Elms and the City in Arthur-street, just near London Bridge, and after the trains had started we were surprised to find that a stray current flowed which interfered with the working of the telegraph. We found that the addition of a resistance to the circuit reduced the stray currents from the electric railway so that it did not interfere with the telegraph. The voltage of the working battery was increased to compensate for the added resistance. We generally find that there are two sorts of interferences, for short distances and for long distances. I am more interested in short distances because of the signalling and block circuits on the line which are, of course, very much more important than telegraph circuits. We find that for all these short circuits the only remedy for stray currents is to provide insulated metallic circuits. In the electrified area and in the neighbourhood of London, and also many places in the vicinity of tramways, we have to provide metallic circuits throughout for both telegraphs and signals for short distances. Short-circuits on electric lighting systems are sometimes very serious in their effects. For instance, a short time ago the main switch of an electric motor in a saw-mill was put to earth, with the

result that all the earth circuits for three miles around were affected. On one of our telegraph circuits between London and Shepperton we have to add a resistance of 900 ohms in order to reduce the stray currents sufficiently. As a matter of fact the earth all over the country has a difference of potential from one spot to all others, and this potential varies continuously. Table A gives some of the measurements which I have taken. Although telegraph engineers have asked power engineers to give them consideration, I think that they themselves have to give consideration and readjust their apparatus so as to come into line. On the South-Western section of the Southern Railway we have numerous telephones over the electrified area and there is no interference at all. As to the proximity of the telegraph wires and telephone wires to the power line, with a railway it is rather a serious question to separate them widely; as a matter of fact it can hardly be done without widening the railway. In some cases where the Brighton and South-Western sections run parallel with the Brighton section electrification we thought that there might be some trouble, but on the telegraph lines on the South-Western section, running parallel with the Brighton electrification at Clapham Junction, no effect whatever was found.

TABLE A.

Difference of Potential between Towns, as measured by Stray Earth Currents.

Circuit	Distance	Resistance of circuits tested	Average current varying in direction	Occasional momentary value of current	Difference of Potential
	miles	ohms	mA	mA	volts
Waterloo–Woking	24·5	312	2 to 6	20	0·624 to 1·872 and 6·2
Waterloo–Guildford	30·0	202	4 to 10	20	0·81 to 2·025 and 4·05
Waterloo–Portsmouth	73·25	803·75	0 to 10	15	0 to 8·03 and 12·02
Waterloo–Salisbury	83·75	3 247·5	0 to 3	—	0 to 9·74
Waterloo–Exeter	171·5	7 000·0	0·1 to 0·4	—	0·7 to 2·8
Exeter–Waterloo	171·5	7 000·0	0·2 to 1·0	—	1·4 to 7·0
Waterloo–Exeter	171·5	6 675·0	0·16 to 0·4	—	1·068 to 2·67
Waterloo–Exeter	171·5	3 524.0	0·2	—	0·7048
Waterloo–Southampton ..	78·5	2 285·25	0·1 to 1	—	0·2285 to 2·285
Waterloo–Dartford	19·0	2 634	nil	—	—
Waterloo–London Bridge ..	1·25	1 500 ohms added to circuit which was dispensed with when circuit put through to Dartford.			

Tests were made on different days. The stray currents varied in strength and direction continuously during each of the tests.

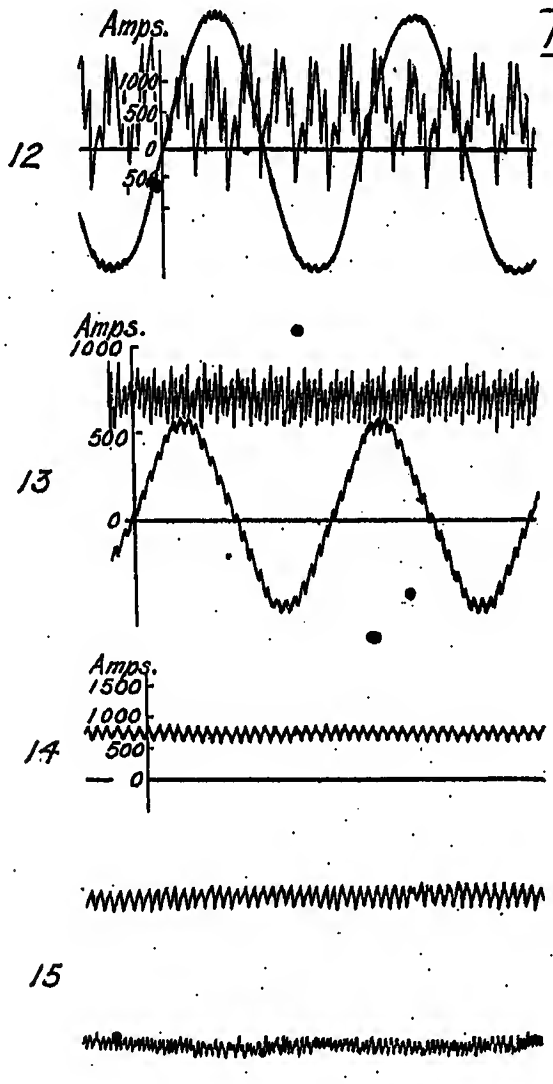
Mr. R. A. Mack: The subject of interference has grown during the past 10 or 20 years from one of interest to one of very great importance. I do not think that it is an exaggeration to say that from the points of view of both power and communication engineers it is one of the big problems which demand careful consideration and which justify considerable expense and investigation. The paper deals almost exclusively with communication circuits over open wires. It is hard to understand the reason for this, seeing that the majority of telephone lines now being put down in this country, in Sweden, in Switzerland, in France, in Italy, and in practically every country in Europe, are not open-wire lines but cable circuits. The author may reply that with cable circuits one can neglect interference; in fact, on page 820, in one of the few references that he makes to cable circuits, he says, after referring to certain disabilities present in the case of open-wire lines: "Circuits in underground cables are, of course, not included in the above list of disabilities." With telephone or telegraph cables, provided the sheaths are earthed, electrostatic induction is, of course, eliminated and the standard of precision in the manufacture and installation of good modern telephone cables is so high that the effects of electromagnetic induction are very materially reduced. Cables, however, are not a certain cure. The author refers on pages 846 and 847 to two good examples which show very clearly that one cannot regard cables as a means for completely avoiding inductive interference. On page 822 circuits for noise measurement are given, but that illustrated in Fig. 3 dates back, I believe, to 1913. There is an instrument using a later circuit, now widely employed in America and in Europe, which is more portable and with which very good work has been done. In spite of the inherent difficulties in obtaining precision with noise measurement, this instrument in the hands of the Bell System engineers has enabled a fairly complete technique in noise measurement to be developed. It is now possible to predict with fair accuracy the influence upon intelligibility of a given amount of noise. The circuit of this instrument was described in a recent paper* on "Transmission Maintenance of Telephone Systems" before this Institution. It is important to remember that the "noise unit" in which this instrument is cali-

* *Journal I.E.E.*, 1924, vol. 62, p. 658.

brated is but one-twelfth that for the circuit described by the author. On page 845 the author touches on the question of the relative advantages, from the inductive-interference standpoint, of d.c. and single-phase a.c. systems. I am not sure that it is altogether fair to refer to this question in a paper which does not mention electrolysis, although the title may perhaps give just cause for expecting reference to electrolysis. But whether or not his remarks are correct regarding the single-phase system having given more trouble than the d.c. system, it is, I think, quite fair to say that, if such be the case, the single-phase system or the communication systems which he has in mind are badly designed. There are examples in Europe which indicate definitely that the single-phase traction system can be run parallel with and in close proximity to a communication system without causing difficulty. The first lantern slide shown by the author indicated a typical condition in Switzerland where the routes of the power system and the telephone system cannot be separated. In Switzerland there are cases of single-phase traction working over routes with very steep gradients and in close parallelism with communication circuits, where noise causes no difficulty whatever. In some cases it has been necessary to install high-grade telephone cable to ensure this immunity. The same point is indicated by the recent decision in Sweden to employ the single-phase traction system on the railways, notably the line from Stockholm to Gothenberg. It is of interest to remark that in this case the Administration have decided to use a cable laid actually alongside the rails from Stockholm to Gothenberg, a distance of approximately 300 miles. Provided that proper care is taken with the power or traction system, whether a.c. or d.c., and provided also that proper care is exercised in selecting the right telephone system and material, there is no reason why adequate protection from, or avoidance of, these difficulties cannot be obtained. I am not sure to what extent British manufacturers of power machinery have given close attention to this matter, but I suspect that some of the Continental manufacturers are ahead of them. Some Swiss companies in particular have considerable experience in the design of machines which are free from interfering effects. On page 839 the author states that "a properly balanced circuit for commercial purposes is taken as one which would be undisturbed by other telephone or telegraph circuits working on the same route." This remark might give the power engineer the impression that the telephone engineer is content with his circuits so long as they do not interfere one with the other. If a power engineer does get that impression, he is certainly getting the wrong impression, as modern telephone plant provides numerous examples of features in which the telephone engineer is providing something to take care of the liability of power interference. The precision methods now employed in the manufacture and installation of modern long-distance cable systems are to some extent the outcome of the necessity for reducing this liability. Numerous cases could be quoted where the balance upon communication circuits is to a considerably higher standard than is necessary from considerations of interference between communication circuits. Two further examples which might be cited are the use of the three-coil system for loading phantomed circuits, and the utilization of dust cores in loading coils. The three-coil system ensures that any current which may be induced from a power system influences both sides of the phantom circuits equally and so avoids a condition of unbalance which would result in serious power interference upon the phantom circuits. With alternative systems, notably the four-coil system, this condition does not exist, and a telephone system using this type of loading is liable to serious interference. The use in loading coils of cores made from very fine, insulated particles of iron dust ensures that the risks of core magnetization from induced currents are reduced to a minimum. There is, of course, a great deal of information yet to be gathered upon the general subject of power interference before the best economic solution for its prevention in any given case can be determined; and in this work much investigation by both power and telephone engineers will be necessary. The greatest factor towards the satisfactory solution of the outstanding problems will be a spirit of helpful co-operation between these two bodies of engineers.

Mr. G. V. Twiss: The author deals with the matter of single-phase systems where uninsulated earth returns are used, and shows that such systems are particularly disadvantageous from the point of view of communication circuits. It is sometimes thought that single-phase systems using uninsulated earth returns may present advantages in the matter of giving supplies to small villages and outlying rural districts, but I think that that is rather a short-sighted view, as such a system can only be economically justified so long as the transmission lines are less than fully loaded. When full electrical development does come—and I imagine that it must come to this country—I think that it will be found that the more normal three-phase systems will be far more suitable. Therefore, although I think it is sometimes held that the Postmaster-General is at issue with the industry on this point, nevertheless in my opinion his view does not conflict with the interests of the electric supply industry. Then, as regards the use of the more normal three-phase systems, the author shows that inductive interference is largely due to earthing, but then apparently only due to residuals in the three-phase circuit, which residuals in turn are chiefly due to the presence of harmonics, when the connections of the transformers are such as to permit the propagation of such harmonics in the line. From that may be deduced the attitude of the Postmaster-General in respect to the matter of earthing. There are so many advantages to be obtained from earthing that it seems to me that the first thing to do is to make provision for earthing, and then to find means whereby earthing will not lead to results harmful to communication circuits. That seems to me to be the correct method of attacking the problem. The recent 220 000-volt systems in California could not run unless they were earthed. Turning to the legislative side, it would seem that permission to earth is something which the Electricity Commissioners themselves can give, subject, however, to the concurrence of the Post-

master-General, which is liable to be withdrawn at any time. It would be extremely unfortunate if the Postmaster-General were ever to exercise such right. In view of the fact that such interference as already indicated is due to other things than earthing, I am surprised that the Postmaster-General should pick out that one thing and disregard the other questions of harmonics and transformer connections, particularly in view of the fact that in Section 69 of the 1899 Act it is made incumbent upon undertakers to see to it that their lines and works—which presumably include such things as transformers, etc.—shall not harmfully affect the communication circuits of the Postmaster-General. That would seem to be an umbrella under which the Postmaster-General can always shelter, and it is difficult to know why he wants another and smaller umbrella, as it were, to catch the drops that might fall off the larger one. There is still another aspect of the case. The Commissioners, if they think fit, in cases where they deem earthing to be necessary for the safety of the public, can give authority therefor without any reference to the Postmaster-General. I do not think I am alone in the view that earthing is in all cases a matter which affects the safety of the public. It is a concomitant of protective systems, and as regards overhead lines it gives a more certain method of causing the line to be shut down in emergency. It would seem, therefore, that the whole matter of earthing could stand, as it were, upon the basis of safety of the public. As regards the protection of the lines, the requirements of the Postmaster-General differ from those laid upon undertakers by the Electricity Commissioners. All these things add to the difficulties of the industry, and in my opinion some of them are difficulties which we ought to try to avoid. In that connection the author refers to the development which he thinks will come about in this country. I would supplement what he says in this matter. In my view the development of the electrical industry in this country is a vital matter. It is essential that development shall take place on lines far bigger and broader than we have ever contemplated. In my opinion we shall never achieve the full development of this country, not only electrically but nationally, until we have adequate interconnections, networks and distribution systems generally on the broadest possible lines. It is therefore very apropos that the author should have ventilated the possible effect of development of electric supply upon the Postmaster-General's lines, at a time when such development is still immature, and whilst it is, therefore, not too late to endeavour to apply ameliorative measures.



MACHINE	PARTICULARS	HARMONICS
No. 4	Direct current in negative lead	6 & 24
No. 2	Direct current in negative lead	12 & 36
No. 4	Direct current in positive lead	24
No. 4	Direct current in negative lead Direct current in positive lead	

Fig. D.

Mr. A. J. Aldridge (*communicated*): The author has referred to a telephone interference-factor meter

suggested by Mr. H. S. Osborne as a result of investigations carried out in America.* It is an arrangement whereby the disturbance on telephone lines caused by different frequencies in alternator harmonics is measured. Different frequencies produce different effects on telephone lines, and the measuring device "weights" accordingly the different frequencies occurring in the alternator waves. Fig. 1 in the paper shows the curve on which the "weighting" is based. A warning is necessary as to the use of such an instrument. Fig. 1 is practically an average resonance curve for a telephone receiver of the present day. Should this curve change —15 years ago the average resonant frequency of a receiver was about 750 periods instead of 1 100—the "weighting" allotted will be quite wrong. I think that it is a mistake to rely entirely upon a variable factor such as the receiver resonance point to obtain the relative disturbing effect of different alternators. A second test should also be made without this weighting, as mentioned on page 822. On pages 826 and 827 the author refers to the use of resonant shunts to eliminate harmonics. Can he give us any further information as to the construction of these shunts and as to their real effect? In many supply systems the equivalent station load will be a small fraction of an ohm, and to be effective the resistance of the resonant shunt must be much lower than this. One would anticipate some difficulty in building at a reasonable cost an inductance coil having the desired characteristics. What is the attitude of the supply authorities towards this remedy? As showing the magnitude of these high-frequency currents which may be circulating quite unknown to the supply authorities, I should like to draw attention to Fig. D. This shows the current (nominally direct) flowing between the station busbars and two rotary converters supplying them, in a tramway system. Rotary converter No. 4 was supplied from a three-phase transformer, and converter No. 2 from three single-phase transformers, all fed from one alternator. The low-frequency curve is simply a timing wave. Three points should be noticed: (1) The magnitude of the ripple; (2) the difference in the ripple from the two machines; and (3) the difference in the ripples in the positive and negative leads of machine No. 4. The two curves marked 15 were taken simultaneously each from 100 turns of wire wound directly over the respective cable leads, close to the machine. The oscillograph strip showing the smaller curve was very slightly more sensitive than the other. I should be glad to know whether the author has encountered any similar occurrence and can give any explanation of the effect.

* *Proceedings of the American Institute of Electrical Engineers*, 1919, vol. 38, p. 261.

Mr. J. Collard (*communicated*): In discussing the methods of minimizing telephone interference the author points out that none of the remedial measures so far devised for application to the telephone circuit is suitable for use with public telephone systems. The only means at the disposal of the telephone engineer, therefore, apart from those measures applicable to the power system, is an improvement in the balance of the telephone circuit. This necessity for a high state of balance in telephone circuits exposed to induction from power circuits is brought out very clearly on page 839, under the heading "Telephone Circuit Balance." The great importance of telephone circuit balance being recognized, it becomes necessary to devise some method by means of which this balance may be measured, so that, where necessary, definite values may be specified and circuits may be tested to determine whether their balance is above or below the permissible value. A suitable method for accomplishing this on a circuit subject to interference was described in a recent paper * on "Transmission Maintenance of Telephone Systems." Briefly described this method consists in the measurement, by means of apparatus described in the paper, of two values of noise, (*a*) the noise between the two wires of the circuit, and (*b*) the noise between the two wires of the circuit in parallel and earth, a resistance of 100 000 ohms being connected in series with the receiver for the second measurement. Since the latter value of noise is a measure of the total noise-producing power of the disturbing circuit, and the former value is a measure of the actual noise produced in the telephone circuit, the ratio of the noise to earth to the noise between wires is a measure of the freedom of the telephone circuit from interference. In other words, it is a measure of the balance of the circuit. A telephone circuit having a high value of "noise ratio," as this ratio of noise to earth to noise between wires is called, will therefore be one having a high degree of balance, and hence will be subject to only a relatively small amount of interference. A circuit having a small value of "noise ratio," on the other hand, would be one that is poorly balanced, and one, therefore, that would be very liable to interference. As an illustration of the values of "noise ratio" that may be obtained in practice it is of interest to note that for open-wire lines a value of about ½ is usually obtained, although this value may rise to as high as 2 for a well-maintained circuit. In the case of cable circuits higher values are, of course, obtained and values of 20 or more have been measured. These figures show the considerable decrease in the amount of noise disturbances that will result from the use of cable instead of open-wire telephone circuits. In comparing the relative merits of d.c. and a.c. traction systems with respect to their interference with communication circuits, the author states that the a.c. system has been found to give the most trouble. This conclusion is, perhaps, not quite fair, as no mention is made of the d.c. system supplied with power from mercury-arc rectifiers, although a method for reducing the harmonics in such a system is given in an appendix to the paper. This type of d.c. system may give rise to very serious interference with neighbouring telephone circuits, and, as its use appears to be increasing, there is a probability that some trouble due to this type of system may be experienced in the future. As an example of the noise that may be produced in a telephone circuit in close proximity to a d.c. traction system supplied from a mercury-arc rectifier, the case of a mountain railway of this type, for which measurements were made, may be quoted. The telephone line used for communication between the different stations along

* *Journal I.E.E.*, 1924, vol. 62, p. 653.

the route was carried on the same poles as the trolley conductors. When power was supplied from a d.c. generator, communication over this line was satisfactory. When, however, a mercury-arc rectifier was used for supplying the power the noise induced in the telephone circuit was so great as to make communication difficult even between adjacent stations. The noise measured on this circuit by means of the 1-A noise-measuring set described in the paper already mentioned rose at times, when the mercury-arc rectifier was in use, to a value of about 5 000 noise units. This value corresponds to about 400 of the units described by the author on page 823.

Mr. D. M. W. Hutchison (*communicated*): The troubles that may arise due to the presence of third harmonics may in certain cases be very serious, affecting not only the communication lines but also the power lines and apparatus connected thereto. I have just had experience of such a case, the circumstances being as follows: Three-phase current at 2 200 volts supplied by a turbo-alternator was stepped up to 11 000 volts in a bank of three single-phase shell-type transformers connected star-star with the neutral on the e.h.t. side earthed direct. The transmission line consisted of three miles of overhead line coupled to one mile of underground cable which ended on the busbars of a substation. On the first trial run, when the voltage reached 8 000, the isolating switches in the substation cubicles flashed over their wooden operating links to earth. These were removed and boiled in paraffin wax, and on running up again the oil-switch rods caught fire at about the same voltage and two cable joints broke down. It was observed during this time that the filament of a test lamp supplied from a potential transformer and near a bare e.h.t. conductor was vibrating violently all the time current was on and it was therefore thought likely that the trouble was due to third-harmonic over-pressures not apparent on the voltmeters connected to the busbars. The greater part of this trouble was removed by connecting the neutral of the alternator to the neutral of the transformer bank, but this has not entirely eliminated the triple harmonics on the 11 000-volt side, potential transformers being burnt out after a few hours' run, and there is a perpetual brush discharge between the porcelain insulators of the current transformers and their frames. The note from the third harmonics is audible on the telephone lines, which run for three miles parallel to and 70 feet away from the transmission lines. It is probable in this case that the trouble, which appears to be due to electrostatic charges induced by third-harmonic over-pressures, can only be eliminated by supplying the step-up transformers with a tertiary winding on the e.h.t. side or perhaps a three-phase choke coil with an earthed neutral external to the transformer bank but in the substation to act as a by-pass for the third-harmonic currents.

Mr. R. G. Jakeman (*communicated*): As a machine designer I am particularly interested in the harmonics in the power circuits. The slot harmonics in large modern alternators are very small. In turbo-alternators the pressure wave is practically a pure sine wave, owing chiefly to the large air-gap and the large number of slots per pole. In low-speed alternators the slot harmonic can be suppressed by providing suitably-spaced extra slots, which are not used for the winding. In rotary converters there are two chief causes of a ripple in the d.c. pressure; one is the slot ripple and the other a ripple with 6 times the fundamental frequency, caused by the variation of the armature M.M.F. during a cycle. By careful design the slot ripple may be made quite small, but it can never be

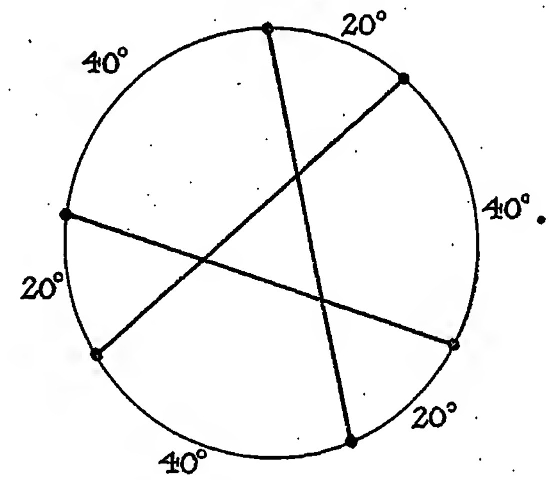


FIG. E.

wholly suppressed in an ordinary 6-ring rotary converter. The reason for this is that the slots per pole-pair must be a multiple of 6 in order that adjacent tapping points may be at 60 degrees to each other, so that the slots per pole must be divisible by 3 and therefore a whole number. By spacing the 6 rings as shown in Fig. E,* the slots per pole-pair are a multiple

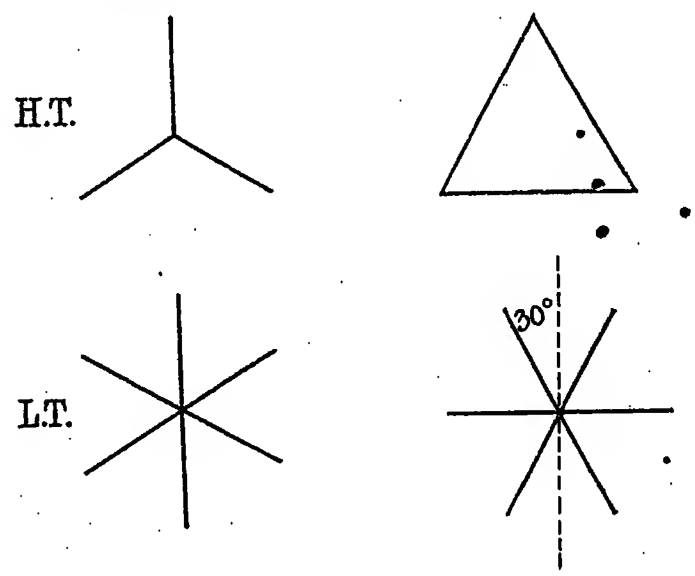


FIG. F.

of 9. Hence, the slots per pole are a multiple of $4\frac{1}{2}$ and may be fractional. This has the effect of suppressing the slot ripple. It will be noted that the three phases are at exactly 120 degrees to each other. This arrangement of the tapping points also reduces the sixth-frequency ripple. The method does not give a neutral point for three-wire balancing, but this is not usually necessary in a traction supply. With a 50-period rotary converter, the sixth-frequency ripple corresponds to 300 periods, which is within the range of speech frequencies. It is impossible to suppress it in a single rotary converter, although it may be consider-

* Provisionally protected.

ably reduced by correct design. In the case of two rotary converters connected in series on the d.c. side, this ripple may be practically eliminated by the arrangement shown in Fig. F.* Each converter is supplied by its own transformer, the primary of one transformer being star-connected and the other delta. As is well known, this provides a difference in phase of 30 degrees between the secondary pressures of the two transformers. The result is that the sixth-frequency ripples of the two converters are displaced by 30 degrees, so that they oppose one another and counterbalance (Fig. G). Since the two armatures are displaced by 30 degrees, the slot ripple can also be eliminated if 30 degrees corresponds to a fractional number of slots, i.e. if 60 degrees corresponds to an odd number of slots. The same effect can be produced by using one transformer only, having two secondaries, one connected "diametral star" and the other "double delta." Further, the ripples will be eliminated from the line if the converters are connected in parallel on the d.c. side. In this case the ripples will circulate between the two machines. A similar effect may be produced with two mercury rectifiers by connecting the primary

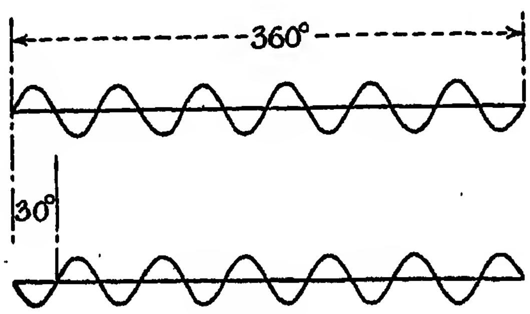


FIG. G.

of one transformer star and of the other delta. In this case two curves like that in Fig. 44 will be displaced by 30 degrees and added, the result being a very much smoother curve.

Mr. S. A. Stigant (*communicated*): The paper seems to indicate that the chief offenders in respect of harmonic interference with communication circuits are rotating machines, particularly main generators. It is perhaps in the nature of things that this should be the case, and so far as one can see at present those features of design which cause harmonic trouble must unavoidably be present in some degree, although by skilful design their effects can be greatly minimized. With transformers, however, the case is different in so far that all harmonic phenomena can be avoided by the simple expedient of reducing the induction density in the magnetic circuit, or, as the author phrases it, by reducing the impressed volts per turn. This procedure would effect the desired result without any reference whatever to the type of magnetic circuit or the connections of the windings. It would, however, naturally increase the dimensions and weights and consequently the costs of the transformers. Actually, there is no need to reduce the induction density below the figures which are now in common use, as harmonic phenomena may also be reduced practically to the point of elimination by suitable connections of the windings. The author on page 852 briefly outlines the influence of transformer connections upon third harmonics, and points out that a delta winding short-circuits third-harmonic pressures, thereby allowing the circulation therein of third-harmonic currents, and that the three-wire star connection may possess third-harmonic pressures either from the neutral to earth or from each line to earth according to whether the neutral point is insulated or earthed. The author also states that there are small residual third-harmonic pressures present on the star side with both the star-delta and delta-star connections. While this is correct from the rigidly theoretical standpoint, I should have thought that inductive-interference effects from these residuals were not only "unusually small," but absent. Can the author give some figures bearing upon this as a result of his own experience, at the same time stating the types of transformer (i.e. core or shell) and whether three-phase transformers or three-phase groups of single-phase transformers were used? Transformer designers have always considered that for all practical purposes a delta winding on either side or a tertiary delta winding short-circuits the third-harmonic pressures so effectively as to leave no residuals worth mentioning. A four-wire star connection similarly considerably reduces third-harmonic pressures, as the fourth wire from the neutral point permits a circulation of third-harmonic currents. In this case, however, there will be larger residual third-harmonic pressures corresponding to the additional impedance between the transformer terminals and the rest of the four-wire circuit. This applies whether the four-wire star-connected circuit is on the primary or the secondary side. With a star-star-connected three-wire circuit considerable third-harmonic pressures may be present, depending upon the form of the magnetic core. With a three-phase shell-type transformer or with three-phase groups of single-phase transformers, third-harmonic pressures having amplitudes of as much as 60 per cent of that of the fundamental may be found when the windings are star-star connected for three-wire service. This is so, as in both these cases the magnetic circuit of each phase is closed upon itself and independent of the other two, so that the flux and, therefore, the induced pressures provide the third-harmonic component necessary for the complete magnetization. In this connection it is worth emphasizing that harmonic phenomena in transformers are due almost entirely to the varying permeability of the sheet-iron used, and very little, if at all, to the hysteresis of the iron. With three-phase core-type transformers, however, third-harmonic phenomena are certainly negligible and in many instances practically absent on account of the magnetic interaction between the cores through the common yokes. Therefore the star-star connection of three-phase core-type transformers should prove perfectly satisfactory in service under any normal earthing conditions. From Fig. 1 it would appear that the relative interference effect at the triple frequencies which are likely to occur on systems in this country are almost negligible, so that transformers are by no means the principal offenders in causing harmonic interference. It is to be expected, therefore, that the earthing of generator neutral points

* Provisionally protected.

is most conducive to trouble, and this appears to have been the author's experience. This aspect should, therefore, have an important bearing upon the question of multiple earthing. If multiple earthing could be effected at transformers alone there seems to be no doubt whatever that the resulting harmonic phenomena causing interference would be restricted to innocuous magnitudes. On the other hand, the requirements of the different protective systems sometimes make it imperative that the neutral point of at least one of the generators actually in commission should be earthed, and therefore the earthing arrangements must necessarily be of the nature of a compromise. If, however, multiple earthing can effectively be adopted without earthing generator neutral points, as appears to have been done in the very home of automatic discriminative protective-gear systems, then the outlook for a wider application of this most desirable procedure is very bright indeed. It would appear that multiple earthing is bound to become more prevalent in this country on account of the increasing interconnection of power stations and networks and the consequent increase in transmission pressures, and it is hoped that the lead given by the North-East Coast power companies will be followed in other places. I am under the impression that interference with communication circuits becomes most severe and at times possibly dangerous when a fault occurs on the power system. Multiple earthing should therefore be very helpful in this respect, as it would enable the fault to be disconnected more rapidly and surely, while the fault currents would probably be weaker (and so less dangerous) on account of the diffusion of the currents through the different multiple paths. While the author gives some interesting data upon the increase of earth currents with multiple earthing, he only gives the current values at the power stations. I do not think that the earth currents are of very much importance at such places, and the vital issue really is to what extent the earth currents diffuse. Can the author give any precise information upon this point? Certainly we are told that under the conditions existing on the North-East Coast, interference to the telegraph circuits under observation was absent and to the telephone circuits inappreciable, but apparently this only indicates the non-proximity of power and communication circuits. The resonant-shunt method of eliminating generator harmonic pressures shown in Fig. 9 appears to me to be somewhat unnecessary. It is clear that this combination will act efficiently only upon the harmonic for which it is designed, and equivalent results can be attained with equal effectiveness if the resonant shunts are replaced by a three-phase interconnected-star neutral earthing compensator, the neutrals of the generator and compensator being connected together and, if desired, earthed. Although I have had no experience of the apparatus shown graphically in Fig. 9, it would appear that the interconnected-star compensator would be cheaper, and it is certainly a piece of apparatus which to my knowledge has already proved its worth. The author is evidently familiar with this type of apparatus, which he refers to on page 852. In reply to his query concerning its rating, while normally it would carry currents corresponding to the excitation of the system and the circulating harmonic currents, it would have to be designed to withstand the short-circuit currents and stresses which may be imposed upon it under the conditions of a short-circuit at its terminals. The duration of this short-circuit would, of course, be fixed by the setting of the protective gear. If neither of these conditions permitted the manufacture of robust windings the mechanical design of these would be the limiting feature. It may be taken for granted that generator and transformer designers are fully aware of those design features which are likely to cause harmonic troubles, and usually the requisite amount of care is taken with the design in order to minimize these effects. Often, however, the designer is left in ignorance of the operating conditions, and he cannot always be held responsible for any abnormality that may occur due to circumstances of which he had no cognizance.

Mr. G. Wüthrich (*communicated*): The author, no doubt on the basis of the evidence accessible to him, considers the single-phase railway system to be a worse offender than the direct-current system. It is rather unfortunate that the only reference to the biggest single-phase electric traction system in the world, namely that operating in Switzerland, represents a no doubt unintended contradiction to this reproach, in so far as the system in Switzerland is disposed of in a single sentence on page 845 by the unqualified testimony to the effect that it "is very successfully used." Quite independent of the present paper, a few days ago I received from Dr. Behn-Eschenburg and Mr. Kristen a summary of their views on this rather controversial subject, and as these views may be of general interest I give them herewith :—

"In our opinion, the disturbances which are most difficult to contend with, from a technical point of view, are those produced in electric circuits by transient phenomena. The rate of increase or decrease of current, which is a determining factor for the inductive effect in the neighbouring conductors, is in the case of short-circuits and interruptions in circuits occurring in d.c. installations a multiple of that for a.c. installations, if we assume that the generating plant is of usual design and the working pressures 3 000 volts and 15 000 volts respectively. The maximum induced pressures are not reduced by the quick-acting switches; the advantage secured resides in the fact that the duration of action of the phenomena is reduced and the disturbances thus rendered less harmful. The conditions are still more unfavourable in the case of rotary-converter operation and a working pressure of 1 500 volts. When carrying out electrification on a large scale it will, in any case, be hardly possible to provide a service affording entire security so long as communication circuits have to be kept above ground near railways operated with single-phase current, three-phase current, or high-tension direct current. The displacement of these communication circuits overhead, on extensive lines, or the adoption of cables cannot, therefore, be avoided (see also the report of M. Mauduit of the French Commission for Electrification). In view of these circumstances, the question of disturbances in communication circuits cannot be regarded as a determining factor for

the choice of the current system, as it is nothing more than a matter of economical importance for all systems. For large railway installations, data are only available up to the present for the single-phase system, in the case of which the use of cables has been resorted to both in Italy and Switzerland for the most important sections; on the other hand, in Sweden a mixed solution has been adopted in view of certain economical considerations (displacement of lines and booster transformer or cables). For direct-current installations of similar size no such data are available; it may also be added that most of the small installations adapt themselves to the plan of the towns where long parallel lines seldom occur. There is an additional difficulty in the case of direct-current installations, namely, electrolysis, which itself necessitates the displacement of the communication cables away from the track. We would further mention that cases have occurred where the Swiss telephone authorities have prohibited the use of mercury rectifiers for suburban lines, owing to disturbance arising from oscillating direct current. In our opinion, the data so far obtained from tests seem to confirm our views regarding the question of system and communication-circuit disturbances."

It would appear that the transposing of communication circuits into cables represents the only radical protection against the troubles experienced, both with d.c. and single-phase traction systems. The experience in connection with single-phase traction is already vast and fairly conclusive. As regards d.c. traction, certainly with pressures above 3 000 volts, the field has yet to be explored, especially in connection with the subject of the present paper, and also in connection with other phenomena of undesirable nature.

[The author's reply to this discussion will be found on page 872.]

Mersey and North Wales (Liverpool) Centre, at Liverpool, 28 April, 1924.

Mr. A. J. Eames: The chief responsibility for preventing interference with communication circuits must necessarily rest with power engineers and designers, whose efforts in that direction should be supported by the application of such remedies as are within the means of telegraph and telephone engineers. The successful elimination of power interference depends largely upon effective co-operation and goodwill. The difficulties can be readily overcome if cordial relations are established between all the parties concerned. There is not a very great deal that communication engineers can effect, apart from seeing that their plant is well constructed and maintained and that telephone circuits are satisfactorily balanced, and assisting in keeping communication and power circuits as far apart as practicable. An accurately-balanced aerial telephone loop is not easily achieved, and it is still more difficult in practice to prevent interference between telegraph and telephone circuits that are carried on the same poles for an appreciable distance. Attention to these points is essential for ensuring efficient transmission, besides tending to circumvent the troublesome effects of power interference. Similar considerations will apply equally to power plant, and, if given proper attention, the additional advantage of the repression of interference troubles at the source will be secured. The most effective method for eliminating the effects of induction is to adopt the best construction and maintenance standards. There appears to be some tendency to use the word "minimizing" rather too freely, with reference to this subject, as there is no doubt that public telephone circuits, particularly trunks and junctions, cannot be regarded as really satisfactory unless they are absolutely free from extraneous inductive disturbances. The considerable development of the telephone service that is expected to take place in the congested South Lancashire district during the next few years can only be met by the liberal provision of suitably designed telephone cables, or by what will be practically an all-underground service. This will materially help to solve the inductive problem, at least locally. The degree of perfection which has been reached in the design and manufacture of telephone cables, and in their maintenance after being laid, is exemplified by the fact that there is no perceptible overhearing between the circuits in the cables, although there may be hundreds of wires running together for scores of miles, contained in a small circular space 2 to 3 inches in diameter. The achievement of such remarkable results in the balancing of telephone circuits surely renders leakages and disturbances from distant power circuits matters which should be remedied at the source of the trouble. In other words the disturbing harmonic frequencies ought to be eliminated as the result of improvements in the design of power plant. It is noticeable that America is the chief source of the information given in the paper, especially as regards the disturbing influences associated with extra-high-pressure power systems. British authorities are in no small measure entitled to claim credit for the great foresight exercised in establishing important safeguards. In fact, it should be recognized that the regulations ensure protection for the plants of all properly constituted power and communication engineering authorities alike, in preventing chaotic conditions arising. The comparative immunity from danger, and freedom from the worst effects of induction experienced in this country, possibly accounts for the fact that British contributions to the literature on this subject are relatively meagre. This is really an indication that difficulties in this connection are being satisfactorily surmounted. It is significant that specialists generally commence by expressing the view that the greatest possible separating distances should be provided between power and communication circuits, particularly where comparatively long lengths of aerial parallelism exist. All responsible engineers will admit that this ideal is sound. In the majority of cases the older services, telegraphs and telephones, were first in the field. Naturally, when traction schemes mature, the question arises whether the undertakers are

prepared to pay the high costs that may be involved in providing the maximum clearance. The matter resolves itself into questions of economics and expediency, and consequently other measures are preferred, unless the policy finds favour of waiting to see how much power interference with telephones the communication engineer will stand. Apart from this aspect the public highways, if used conjointly, do not usually admit of entirely satisfactory clearances being readily obtained, and it is then a case of adapting measures to the conditions which arise. The method for overcoming interference described by Prof. Marchant in the appendix, was used with marked success at Liverpool. A considerable number of exchange subscribers' lines in one of the Liverpool exchange areas were adversely affected by the harmonic frequencies produced by the mercury-arc rectifier, both when in use for lighting and for traction services. Such troubles may be accentuated where electric lighting services are installed in the same buildings, and where there may be damp walls. With regard to the transposition system for telephone wires, would it not be advantageous where there is parallelism with a traction system to revert to the continuous transposition (or twist) system, in which the wires make a complete revolution every four spans? According to the diagrams there are intervals of from $\frac{1}{4}$ mile to 2 miles between the transpositions. In the first two paragraphs in the section headed "Noise in Telephone Circuits," it is not clear how the assertion that the mean frequency is 800 per second can be reconciled with that further on, viz. that the maximum sensitivity of the human ear is not less than 1 024 per second. The latter is no doubt correct if this sensitivity be also associated with that of the normal telephone receiver. Serviceable frequencies for music range from 16 to 4 500 (7 octaves), and I have seen a statement to the effect, although I do not credit it, that the extreme range for audibility is 38 000 vibrations (11 octaves). Frequencies of 10 000 to 12 000 have been mentioned as being within the powers of an expert. Wireless amateurs would be interested to know to what extent power circuits may interfere with the reception of wireless broadcasting programmes. The use of a search coil is described in the paper. Does the author think that this could be usefully employed in connection with laying ducts with the aid of a thrust boring machine? (The latter is used for boring a way under the ground ready for pushing pipes through without breaking down the surface.) Perhaps the use of a search coil would be a useful precautionary measure to avoid piercing high-tension mains, the existence of which is not suspected.

Mr. T. Cornfoot: One of the most serious disturbances on telephone or telegraph circuits is that of electrolytic action due to leakage from tramway and railway earth-returns. This disturbance or interference is not referred to in the paper. It is exceedingly difficult to counteract and locate because, while the other disturbances described make themselves felt at once on telegraph circuits or can be heard on telephone circuits, electrolytic action is silent and does not make itself manifest until very material and irreparable damage is done, resulting in grave interruption to communications. With the growth of underground systems using lead-covered cables, which are liable to damage from leakage, it would be of interest to learn whether the author regards the disturbance as being serious. Telephone systems are metallic, but with the development of automatic telephony extensive use is made of earth circuits for signalling and dialling purposes. Would any serious difference of potential between two signalling earths, due to power leakages, cause mutilation of the dialling impulses? The author mentions several electric railway systems which have given rise to inductive trouble. In Liverpool we have an electrified section of line between Liverpool and Southport and also between Liverpool and Ormskirk. This system supplies alternating current at 7 500 volts on the feeders at 25 periods, with 650 volts (d.c.) on the live rail, and there has been no appreciable disturbance on the telephone or telegraph circuits in the vicinity. On page 826 there is a reference to a charging current which alternates between the neutral point through the winding of the machine and through the capacity of the lines to earth. It is further stated that in some cases in this country this current is as much as 90 amperes. I am under the impression that a current of this magnitude at such a point is prohibited by the Regulations of the Electricity Commissioners. I should be glad if the author would confirm this view, and state whether there is any method of overcoming the difficulty.

Prof. E. W. Marchant: One of the most interesting parts of the paper is Mr. Gill's curve, Fig. 1, showing the audible effect of different frequences of current. The enormous difference between the effect produced by a sound due to a current at 50 periods and that due to a current at 1 000 or 1 100 periods is very remarkable. The figures quoted (on page 821) as given by Osborne would, I think, be subject to variation in different individuals, and I suggest that it would be valuable if some such records could be obtained for a number of different people. As a rule, older people can hear high-pitched sounds less clearly than younger people can. In some experiments made in the laboratory a few months ago, I found that one of my students was able to hear a sound of over 12 000 frequency which was entirely inaudible to me. With regard to the question of the transposition of lines, I noticed many years ago, in connection with long-distance transmission in America, that it was found necessary to transpose both the telephone and the power lines for reasons which have been clearly explained in the present paper. I am sure that if power station and telegraph engineers consult together with a view to reducing disturbance, a great deal of trouble in the future will be avoided.

Mr. W. Fennell: I am interested in the running of a number of miles of e.h.t. transmission and distribution lines and my experiences so far indicate that eventually a slightly different, and more reasonable, attitude will be taken up by the Post Office in regard to this matter. One can imagine the case of a projected line which can best be run along a route near to that of a few subscribers' branch lines. In a case like that it would appear that the Post Office should give way, but at present the Post Office will try to prevent that line being erected. The present attitude of the Post Office is that they not only claim that all the expenses of such precautions as the Post Office consider to be necessary to protect their

existing lines from danger or interference shall fall on the power undertaking if a second-comer, but they even put forward the claim that if the Post Office, as second-comer, put a line near to an existing power line they can still throw on to the power undertaking all the expense of protection of the new Post Office line. This is considered to be too unjust even for the Post Office, so it is stated that when the Post Office lines are second-comers the authorities will usually, as " an act of grace," charge half the cost. In this connection there is a statement on page 839 to the effect that if the telephone lines were perfect as to design and maintenance they would not be affected by induction from power or other lines. I would suggest that as neighbouring power lines, etc., will have a very much greater disturbing effect on imperfect lines than on good ones, the Post Office are asking others to pay for Post Office deficiencies. The Post Office, of course, have in general erected their lines first and have covered the country with absolutely unprotected overhead circuits, so that if the power engineer is asked to supply power to the inhabitants, say, of an area like the Wirral Peninsula—which can be dealt with economically only by means of overhead electric lines—he will be put to very considerable trouble and expense, involving high charges for electricity if the Post Office are not accommodating. The public interest, in fact, should come before departmental interests. I consider that electric power lines in this country, and especially electric railway lines, are, in general, more important than telephones and are certainly more fixed as to route than are overhead Post Office lines. The Post Office cannot fairly claim to continue to follow railway routes when by so doing they impede or even prevent railway electrification. The same applies to some extent to public roads in relation to electric power and light. The case referred to by the author, of leakages in power circuits upsetting exchange indicators, reminds me of a case which occurred in Cheshire. There was a 50-period overhead distribution system for an outlying residential district. Some consumers in that district insisted that the service lines should go underground from the nearest pole into the residences. These underground services were not properly sealed at the pole and moisture entered the cables, causing rapid deterioration. When these faults occurred the local exchange indicators dropped. Investigation showed that the reason was that neither the supply company nor the Post Office had efficient earth connections, due to the sandy nature of the soil in the locality. I would call special attention to a matter referred to in this paper, viz. the very great effect which an earthed guard wire has in this matter of shielding. Some figures are given in the paper as to the efficiency of one earthed wire running along the side of an electric railway between the power line and the telephone lines. I submit that most cases of static interference due to proximity would be dealt with economically by this method, and no dangerous charging of message wires would be possible if an earthed wire were fixed to each telephone or telegraph cross-arm on the side facing the power line or tramway. This method has its parallel in the armouring of electric cables and the provision of marker boards—to ward off the picks of excavators employed by gas or water authorities—and in the provision of bitumen or other overall coverings of lead-covered cables to prevent electrolysis. The guard wires can be looked upon as the equivalent of armouring and outside insulation. Electric power undertakers do not ask the other road users to pay for these means of preventing interference and it would be well if the Post Office followed the principle of each authority providing at its own cost such means as it thinks fit to protect its own plant.

Mr. C. J. Mercer: To the power engineer the intimation that he is causing interference with telegraphs or telephones not infrequently comes as a surprise and he is inclined to resent any suggestion that he should alter his plant to overcome the difficulty. The paper will have served a most useful purpose if it results in co-operation between power and telegraph and telephone engineers to prevent interference at the source. The author refers to the fact that interference is sometimes carried over a wide area. Such a case came under my notice some time ago. A 7 000-volt three-phase system with overhead transmission was erected parallel with telegraph wires carried on railway poles. The working of the telegraphs was not adversely affected, but the telegraph wires diverged to other routes, and the interference was transmitted by tertiary induction to telephone lines which did not themselves approach the power lines. I have heard the distinctive note of this interference more than 100 miles from the power lines. The trouble was clearly due to harmonics.

Mr. L. Breach: It is not clear from Fig. 43, which refers to the neutral currents on the Newcastle Electric Supply Co.'s system, where the system was earthed when the tests were made. As the figure refers to the 20 000-volt system, it would appear to refer to the leakage on that part of the system only, and not on that part which is coupled to the 6 000-volt supply, and it does not refer in any way to the leakage at the neutral point of the alternators. If a diagram were included showing these earthing points, the figure would be more easy to follow. On page 852 the author refers to the earthed neutral as an accomplished fact, and states that "in addition an earth may be required in connection with the operation of protective gear on the power system." It is not quite clear what is meant by this second earth, as of course one earth at the generating station is all that is required for the protective gear, unless the author refers to the earth on the secondary side of the protective gear, which would not appear to enter into the discussion. Referring to the appendix on page 857, I would add that the rectifier caused disturbances on the telephone circuits both when operating on the traction system and when on the lighting system. The disturbance has, however, been entirely eliminated by the methods shown in Fig. 45, but the diagram needs some further explanation. The piece of apparatus D is a choker in the cathode and is of the air-core pattern; this was in circuit originally, as were also the chokers in the anode. The latter were, however, iron-cored, so that some attempt was made by the designers to obviate the possible trouble. The coil with no denotation is of course the auxiliary resistance which is required to supply a load on the rectifier at times of light load on the system. A lantern slide ex-

hibited by Prof. Marchant showed a reactance in the neutral of the alternators and resonant circuits on the phases instead of a resistance in the neutral. This reactance would form a very large piece of apparatus in a modern power station where the current to earth for alternator protective purposes must be equal to the current of the largest alternator installed in the station, and this may be over 3 000 amperes. I should be glad if Prof. Marchant would give us some idea of the size of such apparatus.

Mr. J. A. Morton: It is stated in the paper that, the usual three-phase power lines in this country having balanced currents and voltages and being mostly untapped lines, the interference with open communication wires is at present very small; but in the future the situation may alter. There are likely to be many high-tension supply lines erected in sparsely populated and agricultural districts where nothing but an overhead line would pay and where the loads taken off are at irregular intervals and of quite small amounts, these small loads being almost certainly single-phase loads. This being the case, the currents and voltages in the three-phase transmission line will be unbalanced in different parts of the lines, and the possibilities of interference will consequently be increased, unless the Post Office have by that time put their circuits where they should be, i.e. underground. In the case of bare telephone wires carried on the same poles with, and underneath, power lines, it is quite possible to get good speaking through such wires, provided they are continuously revolved and the insulation is maintained in a satisfactory state. Such telephone lines are, however, likely to be of little use when most wanted, that is to say, when something has happened to the power line itself. At such times the open telephone line is likely to be out of commission also. The best practice is to put the telephone wires in a lead-covered cable, the wires being paired and paper-insulated in the ordinary way, and the lead covering of the cable being earthed. The telephone cable is usually suspended from the longitudinal steel earth wire which is also earthed and which itself acts as an efficient earthed screen between the telephone cable and the power wires. I have never heard of dangerous voltages being induced in a telephone cable carried in this way. The suggestion, on page 843, for a change in earth connections is a useful one. This has been discovered by possessors of wireless receiving sets, who in some cases have reduced the buzzing in their receivers by taking the earth off the water system, which acts as a sort of collector of stray currents, and sinking an old bucket as a separate earth in the garden. On page 851 a case is mentioned in which interference with overhead telephone circuits occurred because the outer conductor of a single-phase concentric cable was leaking to earth at several places. Would the author expect such a state of affairs to cause interference on *underground* telephone circuits, i.e. on paired circuits in underground lead-covered telephone cables? The author mentions that the earth required in connection with the operation of protective gear on some power systems is objectionable, but I fail to see why this should be so. Prof. Marchant showed in his first lantern slide how the capacity current in a power system might cause interference even with only one definite earth on the system, but the protective-gear pilot circuit is usually physically separate from the power circuit, and the capacity current in a protective pilot cable must surely be too small to cause interference. There is, however, one form of protective system in which each pilot conductor used in connection with the protective gear has an insulated copper earth-sheath round it which carries the capacity current back to the station, so that in this case it never gets to the earth at all and could not cause interference. The necessity on both power lines and telephone lines of having the insulation as perfect as possible is very apparent. There are high-tension lines which, although they are the most exposed portion of the electrical plant and work under the most onerous conditions, are never examined until they fall down. Some engineers who keep their station plant perfectly clean and well-maintained seem to forget the power line, presumably because it is not directly in front of them. The consequence is that insulators get covered with soot or salt and that the line insulation is not properly maintained. Leakage caused in this way will affect the communication circuits in the neighbourhood. Having said this, I wish to suggest to the author that possibly the Post Office themselves would get less interference if the insulation of their own lines and instruments were better maintained.

Mr. F. J. Teago: Fig. 1 is, in my opinion, the most interesting part of the paper. Further research along these lines might well be carried out in order to ascertain whether the interference curves for other types of receiving apparatus differ materially from that of Fig. 1. Having a set of typical interference curves, one could endeavour, in the design of electric generating machinery, to avoid those harmonics which produce peak values of interference. Fig. 1 appears to suggest that the reason why d.c. machinery does not interfere to the same extent as a.c. machinery is that the harmonics in the d.c. case are of high order and lie beyond the peak, whilst in the a.c. case they are of low order and lie between zero and the peak. I should like to point out that to eliminate harmonics from electrical machinery to the extent desired by the author would be a difficult and expensive matter, and that self-help is usually the most effective form of assistance.

Mr. C. Rettie: I should like to ask the author whether more trouble is experienced with three-phase lines than with single-phase lines. I should imagine that a partial earth on a three-phase system with an unearthed neutral would cause a great deal of trouble. The late Prof. Steinmetz referred in one of his books to the great destructive oscillations that would occur on a 50-mile length if a neutral wire on a three-phase 44 000-volt system fell to within 2 inches of the ground. An arc would be formed and the voltage would drop to 25 000, the arc would go out, the voltage would again rise to 44 000, and this would go on intermittently for hours until the fault was cleared. I should like to refer to the author's remarks on the question of the design of the machinery. In the Report of the Californian Railroad Commission it was pointed out that with the accurate design and manufacture of the machinery many, if not all, of the troubles with inductive inter-

ference would disappear. Are there any difficulties in the way of obtaining that end? Mr. Teago has partly answered that question, and has referred to the difficulties that would be encountered in the design of dynamos to eliminate indefinitely small leakage currents; but it is to be hoped that the difficulties will soon be overcome. I am pleased to note that interference is caused by direct-current systems as well as by alternating-current systems; the disadvantage, being common to both, cancels out.

Mr. S. C. Bartholomew (*in reply*): Before replying in detail to the discussion in London and Liverpool I should like to express my gratification at the manner in which the paper was received. The discussion will add considerably to the value of the paper, as much new matter has been added and the criticism is helpful.

I have for long held the opinion that co-operation between the various interests concerned, referred to by Mr. Stubbs and others, is the only way of solving the majority of the interference problems. Mr. Stubbs points out that there is no specific reference to the work of Prof. Hughes on induction. The investigation of Prof. Hughes and his work have become merged in the general basic theory and I did not think it necessary to refer specially to him. I agree that it might be thought from the wording that the merit for the introduction of the cross-over system rests with America: I did not intend to imply this. As Mr. Stubbs points out, designs based on that system were prepared many years ago and are given in old Post Office Technical Instructions, which do not differ greatly from those shown in Fig. 19. It was not adopted, for the reasons given, but it has certain maintenance advantages over the twist system. Particular wires can be more readily identified and, in the event of a general breakdown, services can be more readily restored. There is also less risk of contact between wires, as in the twist system the clearance is less at the centre of the span. On the other hand, in the matter of power circuit interference the twist system appears to have an advantage. When power circuits are erected in proximity to telephone circuits run on the cross-over system the crossing points in the latter may require correcting to co-ordinate with the position of the power circuit; this is not necessary where the twist system is in use.

Prof. Marchant refers to the relative interference effects of harmonics of different frequency, and asks whether any figures other than those quoted from Osborne are available. I have not seen the results of other investigations. The frequency weighting curve used for the interference-factor measuring set referred to by Osborne is reproduced in Messrs. Erikson and Mack's paper on "Transmission Maintenance of Telephone Systems."*

Mr. Parry calls attention to a disparity between theory and experiment in the case of electrostatic induction produced by the Lake Coleridge–Christchurch 66 000-volt three-phase line on a telephone circuit carried on the same pole line. I had noticed this difference when reading Messrs. Marsden and Caldwell's paper, and the reason for this disparity given by Mr. Parry—that the difference is due to the insulators not being designed to stand a pressure of 3 565 volts—is no doubt the correct one. I wish to thank Mr. Parry for the additional curves given of the induced voltages produced by two 11 000-volt power lines by electric and magnetic induction upon a neighbouring telephone circuit with various separating distances. There are one or two comments which I should like to make on this. The calculations are based upon the effects of balanced voltages and currents, which effects can be greatly reduced by transposing the power wires and the telephone wires. The most frequent causes of trouble are, however, due to the residual voltages and currents, upon which the transposing of the power wires has little effect. Moreover, as 11 000-volt lines are referred to, these would in most cases be fed directly from generators with neutral points earthed, and are thus more likely to be carrying a residual voltage due to the third harmonic or multiples thereof, which would be more objectionable than the balanced voltages and currents, and the values are usually unknown beforehand. As regards the separating distance between the power and telephone lines in this country, the minimum would rarely be less than the 66 ft. referred to, as for safety reasons, i.e. to guard against the possibilities of contact, this separation must not be less than $1\frac{1}{2}$ times the height of the telephone line, and would usually be of that order. It may be of interest to supplement the information on this point by giving some figures which have been published in America for a rough general guidance as to limiting lengths of parallel for different separations and voltages of supply circuits which, experience indicates, usually will not lead to serious inductive interference in paralleling telephone circuits. The table applies to parallels with 25- and 60-cycle supply circuits without earth connections, with the load reasonably well equalized among phases, and which are not unbalanced to an extent greater than would be caused by the differences in the capacities between the line wires and earth in an untransposed three-phase supply circuit.

Separation	Limiting length of parallel for		
	11 000 volts	33 000 volts	100 000 volts
ft.			
40	1 mile	700 feet	—
100	4 miles	3 000 feet	600 feet
200	15 miles	2 miles	2 000 feet
500	60 miles	8 miles	1·5 miles
1 000	—	25 miles	5 miles

It will be noticed that these figures are also not based on the case of earth-connected power circuits and, moreover, do not take into consideration the effects of faults on the power line. This latter question is becoming of

* *Journal I.E.E.*, 1924, vol. 62, p. 653.

as much importance as that of disturbance produced by the normal working of the power lines. I understand that in Germany in certain districts the administration are in difficulties owing to the number of operators who are asking to be pensioned owing to the acoustic shocks received, which, it is claimed, undermine their health. Much greater separating distances than those given by Mr. Parry or in the table will have to be allowed to prevent these shocks. It is gathered that the worst offenders are not the very high-pressure lines but those of between 10 000 and 20 000 volts.

Mr. Thorrowgood's remarks are in the main confined to leakage currents. It is rather surprising to find that there is "no interference at all with telephones on the South Western Section of the Southern Railway." The alterations to the rotary converters after the line was opened made a great improvement, but when speaking to Mr. Thorrowgood's office at Wimbledon I have frequently heard the same note that is picked up on some of our Southampton telephone trunks when they are slightly out of order. These trunks are erected on the railway line for a few miles. Much depends, however, upon the definition of interference. A short telephone line—not a public line—will be satisfactory with a considerable amount of induced noise, as the speech margin is usually ample.

Mr. Mack finds it hard to understand why the paper deals almost exclusively with communication circuits over open wires, and then gives the answer. The very great majority of cases of interference which I have experienced have been with open lines, and the same holds good apparently elsewhere, due mainly, as Mr. Mack points out, to the elimination of electrostatic induction where underground lines are used. The cases of interference with underground circuits by electromagnetic induction are likely to be confined to telegraphs using an earth return. Mr. Mack is correct in assuming that the noise-measuring circuit shown in Fig. 3 dates from 1913. I was not aware of the up-to-date position on this matter until I read the recent paper * by Messrs. Mack and Erikson before the Institution, which appeared after I had prepared this paper. I agree with Mr. Mack that a proper comparison between the single-phase and the direct-current system of electric traction from the interference point of view would have to take into consideration the effects of electrolytic action on lead-covered cables. Electrolytic action could, I think, be logically brought in as "interference," but the paper was already sufficiently lengthy. In the matter of electrolytic action the advantage is of course with the single-phase system. I tried not to be dogmatic in this matter of interference as produced by the two systems of traction, but I cannot help feeling that, judging from the published experiences, the single-phase system is, at the moment, the more to be feared —not perhaps so much as regards interference with speech as from interference with telegraphs and by producing acoustic shock. The last point may be just as important with direct-current systems when high voltages are employed; up to the present there has been no trouble from the medium pressure usually employed. Mr. Mack in a sense rather supports my view where he states "In some cases it has been necessary to install high-grade telephone cable to ensure this immunity." I do not know of a case where it has been necessary to cable open wires adjacent to direct-current systems, although it has been necessary in some instances to alter the d.c. machines supplying the current as described in the paper. On the other hand, in a paper by R. Liljeblad before the Electrotechnical Congress in Gothenburg (1923) it is claimed that a properly designed single-phase motor should not produce more disturbance than a corresponding d.c. motor.* The matter of telegraph interference remains, however, and as this is produced by the fundamental frequency the design of motor does not come in, and its extent depends upon the lay-out of the traction system. I do not wish to labour the point, but I cannot resist quoting the following from Mr. Mack's contribution. "I am not sure to what extent British manufacturers of power machinery have given close attention to this matter, but I suspect that some of the Continental manufacturers are ahead of them. Some Swiss companies in particular have considerable experience in the design of machines which are free from interference effects." Perhaps British manufacturers do not need my help, but the following extract from the report on Swiss economic conditions by O. A. Scott, H.M. Legation, Berne, issued by the Overseas Trade Department, appears to have a bearing on the matter:—"A sum of $22\frac{1}{2}$ million francs will be expended this year in connection with the displacement of a number of telegraph and telephone lines exposed to the inductive effects of the high-pressure overhead equipment of the railways." This sum is considerable, say £900 000. Further, the mercury-arc rectifier which caused the interference dealt with by Prof. Marchant and described in the appendix, was made by a Continental firm. The examples of precision balancing given by Mr. Mack are undoubtedly of the greatest assistance in preventing power circuit interference, but I was under the impression they have not been developed specifically for that purpose but primarily for the prevention of interference between telephone circuits themselves. The methods refer, however, to cables, and my definition of reasonable balance referred particularly to overhead lines, and the degree of balance that can be obtained commercially in overhead open wires can be fairly expressed as one in which the telephone circuit is undisturbed by other telephone or telegraph circuits on the same route.

I am glad that Mr. Twiss can see no advantage from the power suppliers' point of view in the use of a single-phase system with an earth return. In out-of-the-way districts with no telephones in the neighbourhood it would no doubt be unobjectionable, but there should be few places where there is a supply of power and no telephone service. Mr. Twiss treats the earthing of the neutral point of high-pressure three-phase systems as though it is without question the best arrangement. I know that the majority of power engineers in this country do favour that method of working, but it has not always been so, and even at the present time there are a great number of systems in America worked with the unearthed neutral and it would be an easy matter

* *Loc. cit.*

* See *Teknisk Tidskrift*, 6 October, 1923.

to quote European engineers who advocate it. The legal position as regards earthing of power systems is briefly as follows. Certain earth connections are compulsory on low- and medium-pressure systems under the Electricity Commissioners' Regulations for securing the safety of the public. Other earth connections are permitted by the Electricity Commissioners with the concurrence of the Postmaster-General [see Section 10 of the Schedule to the Electric Lighting (Clauses) Act, 1899]. The earthing of the neutral point on three-phase systems worked with high or extra-high pressures falls under this latter category, and permission has never been withheld to such earthing, subject to it being made at one point on each distinct circuit, and subject also to a proviso that the Postmaster-General's concurrence may be withdrawn at any time. I do not think that the industry has found this irksome in any way, and yet it is a valuable power of embargo that I believe the Postmaster-General would not willingly give up. Mr. Twiss points out that the principal inductive effects originate in the machines or transformers, and suggests that Section 69 of the Schedule to the Electric Lighting (Clauses) Act, 1899, should provide sufficient protection for the Postmaster-General's telegraphs, and that any control of the earthing is unnecessary. As the removal of the earth connection will usually remove all inductive effects from residuals, I may perhaps suggest that Mr. Twiss has reversed the umbrella, and that the earth connection is the larger of the two. Section 69 of the Clauses Act requires the intervention of the Electricity Commissioners, and in my view it is better that the two parties concerned should settle matters directly, which is the usual way. As will be seen from the paper, the cure is usually found without it being necessary to alter machines and transformers, which would in general call for greater expense. If, as suggested by Mr. Twiss, earthing of the neutral point is made compulsory by including it as a requirement in the Electricity Commissioners' Regulations for securing the safety of the public, this would seemingly rule out the use of the paper resistances referred to on page 852. I should not like it to be thought that the proper design of generators and transformers is not the first consideration, but at the moment the control of earthing appears to be the easier way of bringing that about, as, if earthing is of importance, the designs will have to be such as to permit of it being done. Should the Commissioners decide that the safety of the public requires that the neutral point of such systems must be earthed, then the Postmaster-General's concurrence would apparently not be required, but such compulsory earthing might in some cases involve somewhat expensive alterations in other directions.

The interference-factor meter referred to by Mr. Aldridge does not appear to be based directly on the curve shown in Fig. 1 of the paper. The curve was given by Osborne in the "Review of Work of Sub-Committee on Wave-shape Standard of Standards Committee," * and was reproduced as Fig. 8 in the paper on "Transmission Maintenance of Telephone Systems." † This curve is obtained by multiplying the sensitiveness of the average receiver to the same current at different frequencies, by frequency, and this indicates the relative amount of sound interference produced by unit voltage of different frequencies present in the harmonics of the power system. Should the characteristics of the average telephone receiver change as suggested by Mr. Aldridge, this weighting curve will presumably have to be altered with it. The interference-factor meter has been used in other countries than America, but on the other hand the design has also been criticized. It is pointed out that the measuring instrument (thermo-galvanometer) sets up the average value from the currents flowing through the resonance connections. This average value could therefore only be regarded as a standard for the interference effects of the noise if the aggregation of the partial notes in the human ear took place in the same way, and it is claimed that a study of the physiological and psychological processes which come into play during listening does not support this view. I regret that I cannot give the details of the construction of the resonant shunts applied to power systems. One would anticipate difficulty in designing such shunts for use on large units, but there are no doubt many cases where they could be provided at little cost and used with advantage. I have tried them experimentally in two cases across d.c. machines, using makeshift material, with fairly good results, but apart from the case dealt with by Prof. Marchant in the appendix I know of no supply undertaking where they are in use in this country. In America there are, I understand, a number of cases where they are employed. I can give no satisfactory explanation of the curious case referred to by Mr. Aldridge in which the harmonics in the positive lead to a rotary converter differed from those in the negative lead; nor have I heard of such a phenomenon coming under notice elsewhere. Cases are known of superimposed return current in a traction system, where current from a section fed by long feeders from one station enters another station by its negative feeders, flows through the generators along its trolley wires and through the distant cars to re-enter the former station by a shorter feeder on another route.* This does not appear to offer a satisfactory explanation, however.

The experiences given by Mr. Hutchison of the employment of shell-type transformers connected star-star, are very illuminating, confirming in every way the unsatisfactory nature of such a combination from the operating point of view, apart from the interference aspect. The severe effects may be due to resonance, and a tertiary winding would probably provide a solution. It would no doubt be difficult to add a third winding to each core to form the delta, and attention can perhaps be drawn to a variation in which some closed turns (copper bands) are placed round each limb. This method is described by H. De Pistoye.† Success is claimed for the method.

I wish to thank Mr. Collard for his full explanation of the noise-measuring arrangements described in the recent paper by Messrs. Erikson and Mack. I am not quite clear, however, how a ratio between the noise

* *Transactions of the American Institute of Electrical Engineers*, 1919, vol. 38, p. 261.

† *Loc. cit.*

* J. G. and R. G. Cunliffe: "Problems in Traction Development," *Journal I.E.E.*, 1913, vol. 50, p. 692.

† *Révue Générale de l'Electricité*, 1921, vol. 9, p. 557; also *Science Abstracts*, Sect. B., 1921, vol. 24, p. 403.

values as low as ½ could be obtained when measurements are made on open lines. This would imply that the noise on the loop was greater than that between the wires in parallel and earth. If this is correct, then presumably the 100 000 ohms in circuit in the latter case is accountable. In the matter of the relative interference effects of d.c. and single-phase traction, I should point out that communication circuits comprise telegraphs as well as telephones, and it was by giving due weight to the effects on the telegraphs that I was led to the conclusion that, at the moment, the single-phase system is the worse offender. So far as telephone circuits are concerned I should say that in this country more trouble is caused by d.c. systems than by a.c. systems. The further example given of the position of mercury-arc rectifiers in this matter is very interesting, and it is evident that in the early designs sufficient consideration has not been given to this aspect.

Mr. Jakeman's contribution is of particular value as he describes other methods of reducing harmonics in rotary converters and rectifiers than those given in the paper, and these should be of great assistance.

Mr. Stigant suggests that in the case of delta-star and star-delta connections of transformers there should, in practice, be no interference from residuals. I agree that this should usually be negligible. No outstanding cases of such interference have come under my notice, but a characteristic note can be heard in some cases on telephone circuits in the neighbourhood of such systems when the telephone circuits are out of balance. I cannot give particulars of the types of transformers (core or shell) or grouping. I note that Mr. Stigant attributes the harmonic phenomena in transformers almost wholly to permeability and very little to hysteresis. I am not in a position to confirm or challenge this, but I should like to draw attention to the following extract from "Transformer Harmonics," by O. G. D. Dahl, a report dated January, 1923, which was prepared for the Research Sub-Committee of the Committee on Inductive Co-ordination of the National Electric Light Association. "There has been considerable discussion of the causes of the harmonics in the magnetizing current. While opinions on this question have differed a good deal in earlier years, most investigators and engineers now agree that they are caused both by the varying permeability of the iron and by hysteresis, which evidently is the case." The multiple earth connections on the North-East Coast are made at transformers and not at generators. The generators may be earthed, but they are on separate and distinct circuits. I am sorry that I cannot give any information as to the diffusion of the earth currents shown to be circulating when the tests were made. This would no doubt be governed by the make-up of the network in overhead and underground plant, and the type of the latter. Mr. Stigant's comments on the resonant shunt versus the interconnected-star compensator, and on the rating of the latter, are welcome. The last method was tried some years ago at my suggestion in a case where serious interference was being experienced, and proved quite effective. In this particular case there was fortunately available in the generating station a transformer which could be used for the purpose.

In reply to Mr. Wüthrich I should like to point out that the expression "is very successfully used" referred to the operation of the single-phase system as a system of traction on the Swiss Railways, and not to the interference problem. I have unfortunately been unable to obtain much information on the Swiss experience as regards interference, and the summary furnished by Mr. Wüthrich of the views of Dr. Behn-Eschenburg and Mr. Kristen is correspondingly appreciated. It is gathered that transient effects due to short-circuits are the greater difficulty, and that these are just as likely to occur with high-pressure d.c. as with single-phase systems. Further, that placing the overhead communication circuits underground or their removal from positions contiguous to the railways is the only way of neutralizing these effects. This is bad news, although not so bad as it would have been considered a few years ago before the development of the loaded cable and the telephone repeater. Overhead routes for trunk telephone service are not now so essential for providing efficient speaking conditions between all parts of the country, but they are of the greatest value and for some services indispensable, e.g. overhead circuits have to be employed for connections between the stations of the British Broadcasting Company when simultaneous broadcasting is in progress, as lengthy underground cables are not suitable for the transmission of music. Large sums of money were paid by the Post Office for wayleave facilities for communication circuits on a number of railways, and the value of these wayleaves depends upon the facilities offered for the erection of overhead lines. As an example, the old Midland Railway carries what is called the backbone telephone trunk route from London to the North. If, therefore, it were established that the electrification of the main railway routes, whether by the direct-current or single-phase system, meant that all overhead Post Office wires must be removed from the railways, a great deal of work would be involved, and one can foresee the possibility of the clash of interests, which it is not necessary to go into here. I had hopes that solutions would be found to the problems, without resource to such drastic remedies as those suggested.

Mr. Eames asks whether it would not be advantageous, in cases where there is parallelism with a traction system, to revert to the twist system of transposition. If the cross-over points are unsuitably placed in relation to the length of parallelism, a rearrangement of the cross-over points should in most cases provide the more economical solution. As pointed out in the reply to Mr. Stubbs, there is an initial advantage with the twist system in that no subsequent rearrangement is required on the advent of a power line in the neighbourhood. Mr. Eames seems to assume that the mean frequency of speech and the note frequency to which the ear is most sensitive must coincide. The former can be computed by comparison with electrical measurements in which single-frequency currents are employed and which do not involve the use of telephone receivers. Similarly, the frequency at which the ear is most sensitive can be ascertained without the use of telephone

receivers. Lord Rayleigh did not use a telephone receiver in the investigations which led him to the conclusion that a frequency of 1 024 per second was that at which the ear was most sensitive. The possibility of power circuit interference disturbing broadcast programmes has several aspects. There is the local interference which affects receiving sets in the immediate neighbourhood of the power line and which is usually confined to sets near to electric railways. Then there is the more serious interference produced by the high-pressure unidirectional current system used in connection with the electrical treatment (purification) of blast-furnace gases. This electrical process involves the transmission of rectified alternating current at 80 000 volts over a line which is perhaps 300 ft. long, and sets up oscillations at the natural frequency of the line. This may affect wireless reception for many miles around, owing to the natural frequency approaching that of the broadcasting transmission. Next there is the possibility of interference with telephone circuits used for simultaneous broadcasting. The land lines between the broadcasting stations have to be overhead as the transmission of music by long underground circuits is not satisfactory, the reason being that the cut-off frequency on underground lines worked with loading coils and telephone repeaters is between 2 000 and 2 600 per second, which is high enough for speech but not for music. Overhead lines are of course much more liable than underground lines to inductive interference, and any disturbance picked up by the land line will naturally be passed on to the listening public. No doubt many have noticed this on occasion. In one case the transmission of a Paris programme to the London station was virtually spoiled by tramway interference with the land lines. Mr. Eames's suggested use of a search coil to detect the presence of power mains under roadways so that precautions can be taken when using a thrust-boring machine, is timely. I may say that the proposed method had been suggested previously, and coils have been made for the purpose. This is an illustration of the old proverb "It is an ill wind that blows nobody any good," as the unpleasant feature of power transmission which is the subject of the paper is here used as a means of assisting other parties in their road operations. A further use for the search coil would be to show the presence of water and gas pipes, as these are usually carrying current if there are tramways in the neighbourhood.

Mr. Cornfoot notes that electrolytic action has not been referred to in the paper although it is another aspect of the interference problem, and asks whether the disturbance under this heading is serious. I agree that electrolysis is a subject that might properly have been included, but on the other hand it is a matter that lends itself to separate treatment, and in any case to have dealt with it adequately would have lengthened the paper to too great an extent. In answer to the question, I regard the general position of disturbance from that source as serious. The possibility of earth currents interfering with dialling on automatic telephone systems in which earth circuits are employed has not been overlooked, and in connection with the proposed change from manual to automatic working in London an investigation was made to ascertain the extent to which the differences of potential between the "earths" of two exchanges might be caused by electric railways or tramways in the vicinity. Tests made with recording voltmeters showed that potential differences were usually of the order of 1 or 2 volts, but in some cases momentary kicks of the order of 15 volts were registered. There was some doubt as to the true values in these latter cases, as the duration of the impulses was short and the sudden increase in the voltage might cause the needle to swing past the correct point. Apparatus was therefore devised which showed the duration of short impulses and also recorded more accurately their magnitude. During a period of one month a P.D. exceeding 10 volts was recorded twice, and 6 volts was exceeded 13 times in tests between Central and Western Exchanges. It has been estimated that the lost calls due to these earth-potential kicks would not be greater than 1 in 600 000, and that the degree of disturbance would require to be 60 times as great as this before the standard of service would be sensibly affected. Mr. Cornfoot's reference to the Electricity Commissioners' Regulations on the matter of maximum current allowed in the connection to earth of the neutral point is of importance. The regulation in question limits the amount of current to 1/1 000th part of the maximum supply current and was evidently intended to ensure that the insulation should be maintained at a high standard, as if that amount is exceeded it is laid down that steps must be taken to improve the insulation. The regulation was evidently drawn up at a time when the effect of the third harmonic in producing heavy charging currents in high-pressure lines was not known. The 90 amperes referred to has nothing to do with insulation failure, and yet according to the regulations the insulation should be overhauled because of its presence. The regulation in its present form is not up-to-date and will no doubt be recast when the regulations are revised by the Commissioners.

The point raised by Prof. Marchant, that the great difference in sound effects by currents of different frequencies as illustrated in Fig. 1 and by the figures given by Osborne, might be influenced by the personal factor, is to a great extent met by the way in which the investigations were carried out, as a number of observers were employed. The interference currents of different frequencies and amplitudes were superposed on the speaking current of a telephone line, and the diminished speech efficiency was arrived at by means of the ratio of clear syllables received to the number of spoken ones.

I should not like it to be thought that Mr. Fennell's summary of the attitude of the Post Office towards the erection of power lines is entirely accurate. The paper was confined to the technical problems of interference, and makes no mention of protection or safeguards to prevent contacts between communication and power circuits; or of the legal position of the Post Office, or of policy which the legal position decides. Mr. Fennell introduces these other subjects in a somewhat challenging fashion and, whilst not denying their importance, I do not think that this is the right place in which to deal satisfactorily with the matter. I must, however, chal-

lenge the statement that the Post Office will try to prevent the erection of power lines. It is perhaps only necessary to remark that an over-statement has a very weakening effect on the very best case. As Mr. Fennell points out, the perfectly balanced telephone circuit would not be affected by induction from power circuits, but he ignores the converse—that a perfectly balanced power circuit would not affect neighbouring telephone circuits. As explained in the paper, it is not possible with overhead wires to maintain perfect balance—but a very high standard indeed is required to meet the inductive effects from other telephone and telegraph circuits—and it is contended that commercially that is the most that can be expected from the telephone administration. If inductive effects are experienced with the telephone lines up to this standard, then it is considered that the power line unbalance is excessive, and the "deficiencies" are with the power system and not with the Post Office. Mr. Fennell seems to imply that public interest is only concerned with the supply of electricity, and that telephones are a departmental interest only. This is not correct—both services are for the public, and it is of course equally the duty of the Department to see that the telephone service is not saddled with charges which are proper to the electricity service. Mr. Fennell says: "The Post Office cannot fairly claim to continue to follow railway routes when by so doing they impede or even prevent railway electrification." As pointed out in the reply to Mr. Wüthrich, the Post Office have paid large sums for wayleave facilities on many of the railways, and if those wayleaves are rendered valueless by railway electrification—which I hope will not be the case—a difficult situation may arise with which it is not within my province to deal. The use of earthed wires in reducing the electrostatic charging of wires is referred to by Mr. Fennell, and I am sorry that even on this I must differ from him. Mr. Fennell suggests that these wires should be placed on the telephone routes at the cost of the telephone administration; but why not on the power line supports at the cost of the power circuit owner? The analogy of the marker boards and armouring round underground power mains seems quite good, but those are provided by the power main owner and not by the other users of the road. This seems to be sound, as it is only just that the owner of the dangerous thing should guard it, as the marker boards, at least, have to be provided to safeguard other authorities who may open the road. One would assume from Mr. Fennell's explanation that the marker boards are provided voluntarily by the owner of the armoured cable primarily for his own protection, but I have always understood that it was a requirement of the Electricity Commissioners made in the interests of other road users. However that may be, it is pointed out that whilst on the one hand the use of earth wires may be beneficial in reducing the inductive effects from the residual voltages and currents, on the other hand it may increase the effects of balanced voltages and currents by distorting the fields.

Mr. Mercer refers to the interference effects sometimes picked up many miles away from the point of origin, and on circuits not directly concerned. Tertiary induction of this character is very often difficult to trace and the instance quoted of a note being picked up 100 miles from the power circuit is illustrative.

In answer to Mr. Breach, Fig. 43 refers to the currents in the earth connections on the 20 000-volt network only and not to that in the alternator earth connections. I agree that if a diagram had been given showing the earthing points the position would have been clearer. It was not given owing to the length of the paper and the already great number of diagrams. I am afraid my wording was not too clear in the quotation made by Mr. Breach from page 852. I did not wish to convey the idea that a second earth is required for the protective gear, but that apart from other considerations an earth may be wanted for that purpose alone. The additional details given by Mr. Breach concerning the application of the resonant shunt to the mercury-arc rectifier referred to in the appendix are of considerable interest and value. Prof. Marchant's reply to the question as to the size of the reactor used in connection with the arrangement of resonant shunts across the phases of an alternator is as follows:—"It is difficult to give any general figure which would represent the cost of a reactance necessary for a current of 3 000 amperes; each case would have to be dealt with on its merits and the value of the reactance necessary would depend on the amplitude of the harmonic which it was desired to eliminate from the wave-shape of the alternator."

Mr. Morton points out that unbalanced power lines may result when high-pressure overhead transmission lines are used for supplying current to sparsely populated agricultural districts, as loads will be tapped off at irregular intervals, probably by single-phase circuits. This is a problem that must be taken into consideration. It is apparently a feature of distribution in America, and a warning against such arrangements is included in the Report of the Inductive Interference Committee of the National Electric Light Association and Bell Telephone System. Mr. Morton asks whether I would anticipate inductive interference with underground telephone circuits owing to leakage on the outer of a single-phase concentric cable. No such case has come under my notice and, although I think that interference would not occur if the telephone circuit in the cable were balanced to the degree required for telephonic repeater working, it is possible that the paired circuits in the ordinary type of telephone cable might be affected, depending to a certain extent upon the type of apparatus in use. Such interference has been caused by neighbouring cables carrying current supplied by mercury-arc rectifiers, and by cables connected to generators supplying three-phase current with the neutral point earthed. A case of the former type has developed since the paper was read. I am afraid that I did not make the position clear as regards the supposed necessity for earthing at the neutral point on three-phase systems. I have understood that for the operation of certain types of protective gear an earth is required at the neutral point. I know, however, that the earthing is not required solely on that account. If the earthing, for whatever purpose it is provided, results in interference, as it does in many cases, then it is objectionable on that account.

In reply to Mr. Teago, the type of receiving apparatus would doubtless have some influence on Fig. 1, but the main characteristics are decided by the ear. As pointed out previously, Lord Rayleigh's figure of maximum sensitivity was not based on the effect on a telephone receiver. Mr. Teago says that it would be a difficult and expensive matter to eliminate harmonics from electric machinery to the extent desired, and suggests, as an alternative, self-help by the telephone engineer. It is also a difficult and expensive matter to provide telephone circuits that will not be affected by those harmonics, and although self-help is practised it is not out of place to point out that, apart from other considerations, the elimination of harmonics at the source will hold good for all existing and future telephone circuits. On the other hand, if they are not removed the added difficulty experienced in the construction and maintenance of telephone circuits is a continuing one, involving not only initial expense but permanent increase in maintenance expenditure and additional cost in the provision of future circuits.

In answer to Mr. Rettie I should say that more trouble has been caused by three-phase than by single-phase lines. The former system is, however, more extensively used. So far as I know, we have had no trouble from partial earths on three-phase systems worked with the neutral unearthed. Mr. Rettie expresses pleasure at the fact that interference is caused by direct current as well as by alternating current, and says that the disadvantage, being common to both, cancels out. The pleasure is wholly Mr. Rettie's, however, as although the disadvantage may cancel out as an argument it unfortunately does not cancel out in actual fact. From the communication engineer's point of view it would be better if only one system had the disadvantage; it would halve his troubles.

A NOVEL METHOD OF STARTING POLYPHASE SYNCHRONOUS MOTORS. *

By E. V. Clark, B.Sc., Associate Member.

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Summary.

This paper records that while some difficulty may ordinarily be experienced in starting up a polyphase synchronous motor simultaneously with the alternator supplying the circuit, the difficulty is greatly reduced if the alternator is of the asynchronous type; and that with small laboratory plant this method of starting is simple in the extreme.

Further, if the asynchronous alternator has a wound rotor and an adjustable rheostat in its rotor circuit, then the synchronous motor may be run up to speed by the operation of the rotor rheostat, with the asynchronous alternator running at full speed throughout.

A scheme for operating small synchronous motors in a factory with this method of starting is outlined as being technically feasible, though inferior to other methods in general convenience and, therefore, devoid of much commercial utility.

Three fields where this method of starting may be of appreciable or occasional use are cited, viz. technical school laboratories, testing-shops of manufacturers, and emergency use by supply authorities.

A standard method given in the earlier textbooks for starting a synchronous motor is to run it up with the alternator, i.e. to connect it electrically to the alternator while the latter is at rest, to excite both alternator and motor, and then to start the alternator very slowly, giving the motor a start by hand. The motor should come into synchronism and thereupon the alternator may be gradually raised in speed, bringing the motor up to speed with it. The author's students attempt each year this method of starting a synchronous motor in the electrical engineering laboratory of the Adelaide University, but with very little success, as the conditions are unfavourable. The two three-phase machines available for the experiment have very different waveforms, and one has to be considerably under-excited when they are used in conjunction. Thus the synchronizing force at low speed is small, and the motor readily falls out of step if the alternator is accelerated at all rapidly.

It would appear that an asynchronous alternator should be much more suitable for use with this method of starting, since the motor would completely determine the voltage and periodicity of the circuit; while irregularity of the acceleration of the alternator would only mean irregular negative slip, and the torque on the synchronous motor would always be positive. Thus, if once the motor is properly running there should be no tendency for it to slow down and come to rest, unless the alternator is accelerated so rapidly (having regard to the inertia of the motor) that the negative slip becomes

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great enough to reduce the torque below that necessary to overcome the no-load losses of the motor.

Experiment showed this to be the case. There is very little difficulty in starting up the laboratory 5 kW three-phase alternator as a synchronous motor when power is supplied to it electrically by a 2 h.p. three-phase induction motor, used as an asynchronous alternator and belt-driven from a d.c. motor. This induction motor has a wound rotor which may be short-circuited for the experiment. The synchronous motor is excited, the switch connecting it to the asynchronous alternator is closed, and the motor driving the latter is then started. As an asynchronous alternator has no power of self-excitation, it follows that no current flows between it and the synchronous motor. But if, as the asynchronous alternator is started, a moderate hand-turn is given to the synchronous motor, this at once generates an E.M.F. and produces sufficient current both to excite the asynchronous alternator and to keep the motor running. The alternator may now be run up to speed quite rapidly, and the motor will follow with no tendency to "fall out."

With the provision of an asynchronous alternator with wound rotor and three-legged rheostat in the rotor circuit, however, it is not necessary to start up the synchronous motor at the same time as the alternator, since the latter may run at full speed throughout the starting operation. The alternator, not being self-exciting, may be connected electrically to the synchronous motor by closing the main switch, without any circulation of current. The motor is excited and the alternator rotor rheostat is placed on the first notch as if the alternator were being started up as an induction motor. And now, by giving a hand-turn to the synchronous motor, E.M.F. is generated, current flows, and the motor runs up to a speed corresponding roughly to that which would be attained on the first notch of the starting rheostat if the asynchronous alternator and synchronous motor were reversed in position. Also, by cutting out the resistance in the alternator rotor circuit notch by notch, the synchronous motor runs up to speed without any excessive rush of current, only a small kick being observed as each succeeding notch is used.

The simple and easy starting of a synchronous motor in these circumstances is just what one would expect from theory. The torque of an induction motor, for a given rotor resistance, flux and slip, is the same except for sign, whether the slip is positive or negative. Hence if the starting torque of a 50-cycle 4-pole induction motor at rest—i.e. when the slip is 50 cycles per second—on the first notch of its starting rheostat is T, then if we mechanically drive the induction motor at 1 550 r.p.m. and have electrically connected to it a 4-pole synchronous motor running at 50 r.p.m., we have a negative slip of 50 cycles per second and a torque of $-T$ with the same rotor resistance in circuit, provided the flux is the same in the two cases. But on a purely inductive circuit, a synchronous alternator of negligible internal resistance gives a constant current irrespective of speed, since the E.M.F. generated and reactance both vary as the speed. Hence as the resistance in the circuit comprising asynchronous alternator stator and synchronous motor armature is small, quite a small speed of the synchronous motor will cause a considerable current to flow and thereby produce the necessary flux.

Various tests of the two varieties of this method of starting synchronous motors have been carried out in the electrical engineering laboratory of the University of Adelaide with the small plant already referred to. Of the two ways, viz. running up simultaneously with a squirrel-cage type asynchronous alternator, and starting on the rotor rheostat of a wound-rotor type asynchronous alternator, the latter is found to be appreciably the better with the laboratory plant. To run up simultaneously needs considerably greater care, as the d.c. motor starts up very rapidly on the first notch of its ordinary starting rheostat, and the synchronous motor must be given the hand start at just the right moment. On the other hand, if a special d.c. rheostat is used and the first notch allows but little current to flow, the sudden access of load as the asynchronous alternator picks up may cause a drop in speed sufficient to let the synchronous motor come to rest. With the wound-rotor type of asynchronous alternator, the easiest way to start is to run this up to speed, set the rotor rheostat on the first notch (or on that notch which gives maximum torque at the speed adopted), connect the stator to the unexcited synchronous motor, give a hand-turn and then close the field switch. The synchronous motor used in the experiments has very excessive "tooth-lock action," and it is impossible to give the shaft any considerable spin by hand if the field is excited. With a type of synchronous motor having more uniform flux distribution, it would be a matter for experiment to determine whether the final act should be to throw in the field switch or the main a.c. switch. Naturally, excessive power is needed for the hand-turn if the motor is both excited and connected to the alternator, as suggested in the preliminary description of the method.

Tests of starting up a synchronous motor under load were made by belting the motor to a line shaft and thence to a set of three unexcited $2\frac{1}{2}$ kW machines with six bearings and rigidly coupled shafts. It was found just possible to start up on this load, if care was taken that as the rotor rheostat was moved from notch to notch the line current was not allowed to exceed the normal current rating of the asynchronous alternator by more than 25 per cent or so. If this were exceeded, the torque became too small and the synchronous motor came to rest. The motor was much under-excited, so that the stator flux would be considerably below normal.

To test this method of starting on a machine of greater magnitude, experiments were next made upon a rotary converter of 150 kW capacity in one of the converter stations of the Adelaide tramways. This is a three-phase 25-cycle 500-r.p.m. machine; and for the asynchronous alternator set the battery booster of the station was adapted, consisting of a 40 h.p. induction motor with wound rotor, driving a 200-ampere 150-volt booster. Temporary leads from a 100-volt tapping on the battery were connected through a water-bucket starter to the booster, by means of which it was run as a d.c. motor; and the stator leads of the induction motor were removed from its transformers and connected to the a.c. terminals of the rotary converter, the field

of which was separately excited. The induction motor is normally run off the transformers of one of the converters, so that its voltage was suitable. The experiments were quite successful, but it was found only just possible to give the converter the necessary hand-turn. The machine in question is provided with a belt-connected pony motor, by means of which it may be started from the a.c. side. With the belt removed, two men pushing on the pulley and armature barrel-end were not able to impart sufficient velocity to cause the machine to pick up. On replacing the belt, however, the greater facility thereby afforded for an effective hand-turn enabled the same two men to give the requisite start. No attempt was made to measure the required initial speed, but the author's impression is that it was in the neighbourhood of 30 r.p.m., or, say, somewhere between 5 and 10 per cent of the rated synchronous speed in this case.

Starting up was tried both on the rotor rheostat, and simultaneously with the rotor short-circuited. The former method enabled the set to be readily run up to speed for synchronizing on to the transformers. The latter tests showed that the set could be started up about as easily on the alternative method; but the conditions were abnormal, the d.c. starting rheostat of the battery booster set being an improvised water bucket which facilitated the running of the set at low speed but did not give sufficient range of resistance to enable the set to be brought up to full speed under load.

In all these tests it was found desirable to excite the converter field before giving the hand-turn, and to let the closing of the main a.c. switch be the final action when a sufficient hand-turn had been given. The difficulty of turning the armature by hand was much the same, whether the field was excited or not, if the main switch was open; whereas the closing of the main switch made considerable difference, probably due to currents caused by residual magnetism. In this respect the behaviour of the rotary converter was just the reverse of that of the laboratory synchronous motor.

In both laboratory and converter station tests, one fact was as evident as it was unexpected, viz. that starting up was very much easier if the synchronous motor was much under-excited. One would anticipate just the opposite. A somewhat superficial explanation that suggests itself is as follows: At the moment at which the circuit becomes active, whether by closing the main switch or the field switch, it is the synchronous motor which delivers energy to the circuit; and not until the flux of the induction motor is built up does that machine act as an alternator and supply energy. Hence the stored energy of rotation imparted to the synchronous motor by the hand-turn must be sufficient to supply this initial flow of electrical energy without bringing the machine to rest. Now at a given speed the voltage is proportional to the flux, while the current will be almost proportional to the voltage. The time taken for the flux of the induction motor to build up will be much the same at any voltage, since the time-constant of the circuit is but little affected. Thus it follows that at a given speed the energy to be supplied by the synchronous motor will vary almost as the square of its flux. The value of field excitation to give the easiest starting—that is, the minimum hand start—will therefore be the smallest value sufficient to provide enough torque to keep the synchronous motor in rotation. It is very noticeable in the laboratory tests how, at a speed quite sufficient with low excitation, the motor comes to rest with a jerk on switching on too strong a field current.

It will be noted that the line current, which lags relatively to the voltage generated in the synchronous motor by a small angle at the initial moment, must swing round to a lag of about 130° by the time the asynchronous alternator takes charge, since the latter can only deliver a leading current; and further, that as meanwhile the synchronous motor has given out energy and therefore dropped in speed, the frequency must fall steadily during this momentary transition period. A record by an oscillograph showing the waves of current and E.M.F. during the second or two following the closing of the circuit, would be of much interest and might render more evident the conditions required for the easiest starting up of a synchronous motor by this method.

Once the synchronous motor is properly running on the asynchronous alternator circuit, one may of course increase the field strength gradually with advantage to the torque transmitted. It would appear, however, that a sudden increase of field strength would momentarily cause the synchronous motor to give out energy and might therefore pull it up if the speed were too low.

Attempts to start up a single-phase synchronous motor in this manner met with very little success. The same two laboratory machines were used, with one of the three-phase star-connected legs disconnected. By giving the greatest possible hand-turn to the synchronous motor, one could occasionally get it to hold in, but this result was exceptional. The method might prove useful occasionally in running up to speed a single-phase machine that could be driven mechanically to, say, one-quarter full speed, but does not otherwise appear to afford much scope for use.

This method of starting polyphase synchronous motors would appear to have little scope for use in the factory, since it suffers from three defects. First, excitation must be available while the motor is at rest; secondly, a hand-turn or its equivalent must be given at starting; and thirdly, even though the asynchronous alternator may run at full speed throughout, yet there must be no pressure on the mains between the alternator and motor prior to the moment of starting. Nevertheless, it is not impossible to devise a scheme for the operation of a factory with a number of small synchronous motors to be started on this principle and operated from public supply mains. A control centre would be provided from which all motors would be started, and this would be equipped with an induction motor driving both the common exciter for all synchronous motors and also the starting asynchronous alternator which would have two poles more than the motor driving it. This set would run continuously while the factory was working. Each synchronous motor (with the exception of very small ones) would drive its load by means of fast and loose pulley or friction clutch, and would be connected to the control centre by five wires, viz. three a.c. armature

leads and two d.c. exciting leads. The control switchboard would include for each synchronous motor a field switch and rheostat and a three-pole double-throw main switch, connecting to the starting busbars in one position and to the public mains in the other, with intermediate "off" position. Starting busbars would be connected through an ammeter to the stator of the asynchronous alternator, the rotor of which would be wound and provided with a substantial three-legged rheostat. A synchroscope would be connected between the starting busbars and the public mains.

To start any motor, the workman operating it would signal by bell-push that he desired it to be started and would proceed to rotate it by hand. The switchboard attendant at the control centre would put the rotor rheostat of the asynchronous alternator on to the first notch, throw the main switch of the synchronous motor in question into the starting position and then close the field switch of that motor. His ammeter would indicate directly the motor started, and he would then bring the latter up to speed by means of the rheostat in the alternator rotor, keeping, if desired, the motor at the low speed of the first notch until he got a signal to tell him that the friction clutch was closed, or the belt transferred to the fast pulley. As the asynchronous alternator has two poles more than the motor driving it, the synchronous motor will readily run up to synchronous speed with respect to the supply mains; and the operator must synchronize in when throwing his motor switch from the starting position to the running position upon the public mains. He thus has entire charge of all motors, and by varying the exciting current either individually or collectively may keep the power factor in the neighbourhood of unity, or leading, as required. Any motors in the factory which have to start and stop frequently—e.g. crane motors—may be of the induction type and have their bad power factors neutralized by over-exciting the synchronous motors.

This scheme is merely put forward as indicating the technical possibility of operating a number of synchronous motors with this method of starting, for it is fully realized that the complexity of the scheme renders its commercial utility extremely small. In special circumstances, where a large number of small motors was desirable and power factor of prime importance, and where, in addition, labour was very unskilled, it might be advisable to install a system of synchronous motors with centralized starting and a common exciting source; but even under these conditions results could probably be obtained more satisfactorily by using synchronous motors equipped with amortisseur coils so as to be self-starting and self-synchronizing, and providing at the control centre a starting transformer with tappings. This would eliminate the hand starting and hand synchronizing which would appear inseparable from the method of starting by means of an asynchronous alternator.

There should nevertheless be some practical use of this method of starting synchronous motors, and three fields may be cited where it should have possibilities.

(*a*) In technical school laboratories, where it may be used both to illustrate the properties of the asynchronous alternator and to start up synchronous motors for the plotting of V curves, etc.

(*b*) In manufacturing-works' testing shops, to start up alternators in order to parallel them on to the a.c. supply mains, whereupon they may be tested as motors, either running light or by means of a rope brake.

(*c*) In substations, for emergency starting when the normal starting gear is broken down, in cases where an induction motor set is available. For example, Stuart-street station of the Manchester Corporation some 20 years ago contained an induction motor-generator set for exciting the main alternators. By means of this it should have been possible, without any temporary connections whatever, to start up on the a.c. side any motor-generator substation in which d.c. excitation was available, provided that the requisite "hand-turn" could have been given to the motor-generator set.

The author's thanks are due to Mr. W. G. T. Goodman, chief engineer and general manager to the Municipal Tramways Trust, Adelaide, for permission to carry out tests at one of the tramway converter stations; and to Mr. A. A. Watkins, chief assistant engineer, both for arranging the temporary connections necessary to enable the tests described to be carried out on one of the spare sets in the converter station, and for much assistance while the tests were in progress.

THE FIFTEENTH KELVIN LECTURE.

KELVIN AND THE ECONOMICS OF THE GENERATION AND DISTRIBUTION OF ELECTRICAL ENERGY.

By Guido Semenza, Member.

(*Lecture delivered before* The Institution, *24th April*, 1924.)

1. Lord Kelvin, at that time Sir William Thomson, enunciated his "conductor law" at a meeting of the British Association in 1881, that is 43 years ago. I should like to quote the words with which his paper began:

> "The most economical size of the copper conductor for the electric transmission of energy, whether for the electric light or for the performance of mechanical work, would be found by comparing the annual interest of the money value of the copper with the money value of the energy lost annually in the heat generated in it by the electric current."

As we all know, he came to the conclusion, as the result of a simple mathematical calculation, that the most economical area of a conductor is that for which the annual interest on the cost of the copper is equal to the value of the energy lost per annum in the conductor.

The law in this simple form has by some been considered to be of very little practical value because it neglects a number of items, which affect the total cost of the transmission, such as poles, insulators, etc. These items vary with the size of the conductor, and it is, in my opinion, this fact which has resulted in Kelvin's law being restricted to theoretical problems and in its losing, in the minds of most engineers, much of its practical value. I have always felt that this is to be regretted and I am glad of the opportunity of explaining the true meaning of the law.

If, on the one hand, I fully appreciate the honour conferred on me by the invitation to deliver this Lecture, on the other I feel that my task is by no means easy. I am an engineer and not a scientist, and I can only speak as an engineer; I fear, therefore, that I shall not be able to maintain the high standard of previous Kelvin Lectures.

There are, to my mind, two important features which make Kelvin's law very interesting. The first is its relation to the intellectual character of the man whom we are honouring; and the second is the development that this law can receive—and, by some, receives daily—in every kind of calculation relating to electrical matters.

2. We must go back to the time when the law was enunciated, the early days of electrical development, in order to realize its fundamental importance.

In 1881 the Edison incandescent lamp had been shown for the first time at the Paris Exhibition, although it was in existence at Menlo Park two years before, and its appearance at the Paris Exhibition was preceded by much scepticism. Before that time only a few arc lamps had been used, and the transmission of power to a distance was still a dream. True, it had been discussed to a small extent, and in America somebody had prophesied the transmission of energy from Niagara Falls over a long distance, but nothing very conclusive appears to have been done before the experiments of Marcel Desprez, which were started in 1881 and were conducted on a practical scale only in 1885—four years after the time we are considering—when he succeeded in transmitting 50 horse-power from Creil to Paris, a distance of 50 km, but at a very low efficiency.

In 1881 Edison already had in mind a distributing network, and in 1882 one of these became a reality in New York and one in Milan (Italy). I have tried to find out how he calculated the cross-sections of the conductors, and I have come to the conclusion that the only factor taken into consideration was the drop in voltage. From the earliest days networks of mains and feeders were not very simple, and therefore the proper sections were determined by experimental methods, the tests being carried out on a model of the network constructed to a reduced scale. It appears that no economic considerations influenced the determination of the conductor areas. As regards the methods of Edison, his biographers report the following remark by him: "I had not much use for mathematicians either, for I soon found that I could guess a good deal closer than they could figure, so I went on guessing." And so I suppose he did the same in calculating his networks, but I think it is only fair to say that we owe a great deal to Edison's "guesswork."

We can also realize that in those days, when everything connected with electricity was still uncertain and vague, things were done more on an empirical than on a scientific basis. They were years of nervous and intense research. Electric light was a rising star on the horizon, and all sorts of inventors were directing their efforts to the development and perfection of the new discoveries which promised to yield renown and wealth. Many of these pioneers, I am afraid, did not understand the difference between energy and current, and the necessity of accurate measurement was not then felt. At the time of this rush comes the Glasgow professor who calmly put a question which nobody had yet thought about: "How can the size of a conductor be determined in order to obtain the maximum economy from an electric transmission?" I am sure that some of the nervous inventors present at the lecture must have exclaimed: "Why ask such a curious question?"

Sir William Thomson, however, was looking into the future. With his deep knowledge, he clearly foresaw the coming importance of the applications of electricity, he already had the conviction that electrical energy would be transmitted many miles and that electric lamps would be as common as candles, and so he realized the importance of the cost of the conductors used. In his well-known paper of 1881 Kelvin had already discussed the size of conductors necessary to transmit 21 000 h.p. from Niagara Falls a distance of 300 miles, and in the same year he had read a paper on "The Sources of Energy in Nature Available to Men for the Production of Mechanical Effect." He was foreseeing the future and was guiding the others. And Kelvin's law enunciated in 1881 was before its time.

3. That this vision of the future was right, has been proved not only by the present importance of electrical engineering, but also by his having discovered and published an economic law which has, in practice, had wide influence. In fact, recent developments in connection with efficiency in the electrical industry have shown that the great majority of technical problems involved in construction, manufacturing and power generation and distribution, are questions of minima or maxima. We nearly always discover that the limiting conditions of a given quantity are obtained by comparing economic factors acting in different directions and following different laws. It is such conditions that limit the dimensions of our ships, the speed of our trains, the size of our smelting furnaces, and the height of our buildings. The general application of this law might even bring the natural philosopher to suppose that it is inseparable from the properties of matter and energy, which latter are the essential elements of industry. Is it not possible that by more careful investigation the principles governing this law might be discovered? It may be mentioned, for instance, that very few laws controlling matter and energy are of a linear character. Friction, gravitation, every kind of distant action, losses due to electric current, magnetic induction, etc., are non-linear functions; even in geometry, owing to surfaces being quadratic and volumes cubic, contents increase much more quickly than linear dimensions. Laws of this kind may possibly determine the ultimate dimensions of crystals and organic cells, and the sizes of plants and animals.

Kelvin's conductor law is, I believe, the first statement of this general law.

4. It does not appear that Lord Kelvin, occupied, as he had been, with deeper problems, gave any further attention to the subject. This was, however, taken up by Professor Forbes in 1885 and subsequently by Dr. Kapp, both of whom developed the original law with a view to its practical application.

As I have already pointed out, however, the majority of those who, with the increase of electrical applications, had to deal with problems which were continually becoming more complicated, did not fully understand the importance of the law and assumed that it was not of much use to them. They preferred, instead, to solve their problems by tentative methods, or, shall I say—without blaming anybody—by guesswork. Moreover, although by a further development all the variables of the problem can now be properly taken into account, objections are still raised to this method of solution. It is said, for instance, that one cannot foresee the price at which the energy will be sold, and that as the prices of metals are continually varying, so that careful calculations are apt to be upset by the first fluctuation of the market, why trouble to undertake long and complicated calculations when the assumptions on which they are based are so unstable? Others raise the objection that there are, in addition to the economic, many other important considerations in fixing voltage-drops and conductor cross-sections.

Some of the objections I do not propose to consider, as they are opposed to the spirit of engineering. Others are to some extent true, but, even so, it is still a fact that calculations of this kind constitute a very good method for a first attack on a problem, or what is sometimes called a first approximation. We may, for good reasons, depart from the results given by our calculations, but we shall always know where we are and where our calculations are leading us, and we shall in any case be prevented from adopting an absurd solution.

5. Some years ago I expressed the opinion, for two reasons, that calculations of this kind should be made by the graphical rather than by the analytical method. The first reason is that some of the variables of the problem cannot be expressed by a formula, and the second one is that by a graphical method it is easy to see how the resultant function varies in the neighbourhood of its maximum or minimum value. I may add that investigation of many cases has shown that the curve giving the desired result is nearly always very flat in the neighbourhood of its maximum or minimum, allowing, therefore, a certain latitude in the choice of the best cross-section. This is fortunate.

Then, to an engineer at least, graphics tell much more than formulæ. Lord Kelvin used to say, speaking of physical phenomena: "I am never satisfied until I can make a mechanical model." Graphics are to formulæ what models are to phenomena: when a mathematical process is plotted in the form of a curve we can see all its characteristics and satisfy ourselves especially as to the effect of altering one or more of the assumptions.

Kelvin's law to determine the most economical area of a conductor has been largely applied in the last 20 years and some very complicated cases have been treated by means of the graphical method.

The cross-section of conductors to give the minimum capital outlay, or the minimum cost per kilowatt or per kilowatt-hour delivered at the end of the line, i.e. to give the highest return on the invested capital, has been determined, and hydro-electric and steam-plant loads have been studied with the assistance of the amplified Kelvin law. I shall therefore not deal with this matter further, but I should like to show how this law has permeated neighbouring fields and I shall start with hydro-electric plants.

6. In every country in which water power is utilized, some very interesting problems are apt to arise. Water-power plants can be divided into two types: (1) Those which I shall term "continuous-flow power plants," in which the natural flow of a river is utilized without any

correction; and those which I shall call "reservoir power plants," in which means are provided for the storage of water. The necessity of storage presents itself when there is a marked difference between the diagram representing the natural flow of the river and that representing the power demand. The natural flow may be high in summer and low in winter, while the reverse is usually the case with the demand for power. On every power-distribution system there is generally an evening peak, although the flow of water may be constant; hence a reservoir is obviously necessary in order to provide for an annual, a seasonal, or a daily difference, according to circumstances.

The cost of the reservoir is generally a very important item and it increases very rapidly with the height of the dam. Also, the number of kilowatt-hours stored increases with the height of the dam, but not always at the same rate. On the other hand, we know that the above-mentioned difference between the flow of water and the demand for power may also be dealt with by using auxiliary steam-power plants. We are thus faced with the economic problem of choosing between three different sources of energy, namely, a continuous flow of water, which cannot be controlled; a reservoir, which can be controlled within certain limits; and thermal plant, the output of which can be varied at will.

When a case of this kind occurs, it is necessary to ascertain in what proportion these three different sources should be used in order to obtain the most economical result. Instead of treating the problem in a general way, I propose to discuss a particular case to show the application of the method.

Let us consider a power supply from an Alpine river the flow of which is very small in winter, when all the high ground is frozen, and very abundant in summer, when the sun melts the snow and ice. In Fig. 1 the curve ACDC′A′ shows the variation in the flow of such a river. For simplicity, the curve has been so plotted as to show the number of kilowatts available throughout the year. With a view to making this example as simple as possible I shall assume that there is a constant demand for electrical energy for 10 hours a day all the year round. A more complicated assumption can, of course, be made if desired.

It is at once clear from Fig. 1 that unless we have at our disposal either some method of storage or auxiliary plant, we could not supply more than 30 000 kW, that is to say, an output corresponding to the minimum flow during the year.

Let us suppose that on the same river a large reservoir could be built. If a reservoir were constructed of such a capacity as to provide an annual storage represented by the area CDC′, then 40 000 kW would be continuously available and could be sold throughout the whole year. We thus obtain an increase in revenue, but also have a larger capital outlay.

We could also fill up the hollow in the diagram by power from steam plant, or partly from a reservoir and partly from steam plant.

Several economic problems can be considered. Let us suppose that it is very important that the cost per kilowatt-hour should be as low as possible and that the demand for energy is unlimited; and let us ascertain what proportion of storage gives the minimum cost per kilowatt-hour, or, in other words, at what height it is most advantageous to draw the line CC′ in Fig. 1. As the demand for power is, for simplicity, assumed to be constant for 10 hours a day, each kilowatt of demand will represent 10 kWh per day, or 3 000 kWh per year (neglecting Sundays and holidays). In Figs. 1 and 2 a curve MM′ has been traced, the abscissæ being kilowatt-hours and the ordinates kilowatts. This curve shows, for each position of the line CC′, the corresponding number of kilowatt-hours stored yearly in the reservoir, or the stored energy as a function of the rated total output of the whole plant. The first point corresponds to 30 000 kW and the shape of the curve depends upon the shape of the curve ACDC′A′.

In order to build a reservoir we must spend a certain amount of capital—there is land to buy, sometimes even houses to destroy, a dam to build, canals, sluices, dischargers, etc. By making various assumptions as to

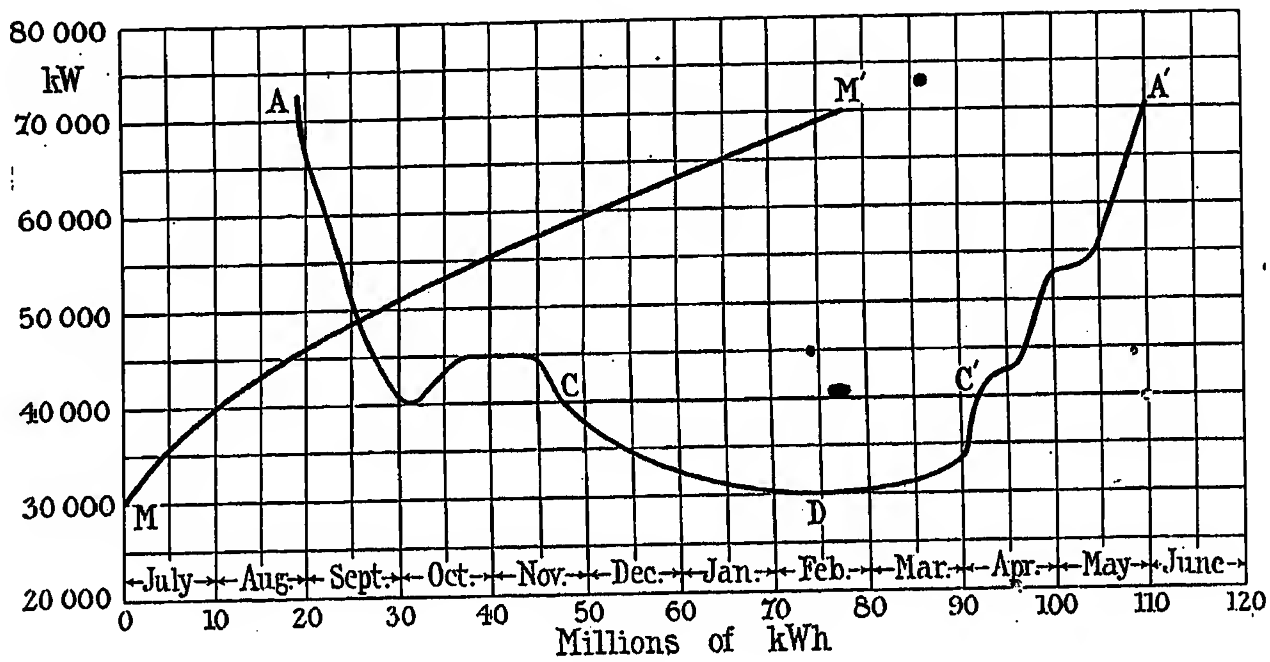

FIG. 1.

the amount of water we want to store, and from the hydraulic data applicable to the case, it is possible to plot a curve showing the capital outlay due to the reservoir, as a function of the total rated power of the plant. We can then derive from this curve the annual cost of the reservoir, that is, the sum of the interest on capital, the sinking fund, the cost of maintenance, labour, etc. Let us suppose that the curve NN′ (Fig. 2) represents such expenses as a function of the rated output of the plant. The abscissæ represent kilowatts, and the ordinates millions of lire.* The curve starts at 1 000 000 lire and does not rise very rapidly at first (which is natural because many expenses are more or less independent of the height of the dam), while it increases more rapidly for higher values of the storage.

Let us now consider the main part of the plant. This consists of canals, pipes, buildings, waterwheels, electrical equipment, etc. The cost of all these items increases with the rated output; and at a very high output it tends to become proportional to the number of kilowatts installed. Let the curve PP′ (Fig. 2) represent these costs. Like NN′, PP′ represents an annual cost. If we add the ordinates of PP′ and NN′ we get the curve POQ, which gives the total annual cost, including the reservoir, the hydraulic equipment and the power house. Dividing, now, each ordinate of POQ by the corresponding number of kilowatt-hours generated in the year, we can plot a curve SS′ showing the cost of these kilowatt-hours. This curve has a minimum value at about 55 000 kW. It also shows that the addition of the reservoir results in a more economical solution than that afforded by the continuous flow alone. In fact, at an output of 30 000 kW the cost per kilowatt-hour is 9·4 centimes, and the most economical output with the reservoir 8·2 centimes, which represents a saving of 11·5 per cent and an increase in the available power of 25 000 kW.

By consideration of this diagram other conclusions can be reached. If, for instance, the cost per kilowatt-

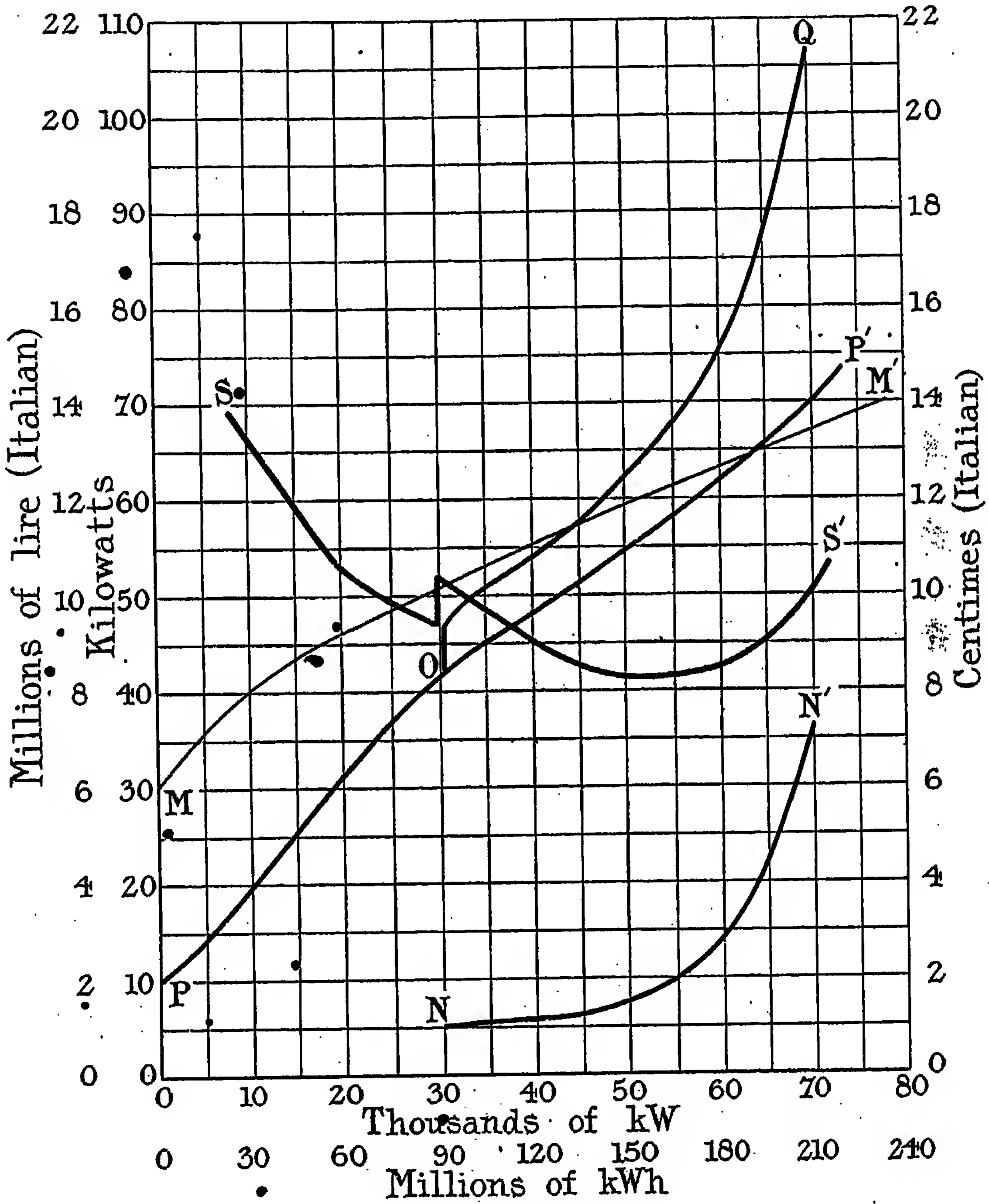

Fig 2.

* At the date of the delivery of the Lecture the rate of exchange was approximately 98 lire to the £.

hour supplied from the plant, assuming no reservoir, is reasonable, it appears that by the addition of the reservoir an output of 65 000 kW instead of only 30 000 kW can be obtained at the same cost per unit. Moreover, by taking into account the capital outlay on the plant, if the selling price of the energy is known it is easy to ascertain for different rated outputs the profit per unit, also the return on the capital outlay, and so on.

Now, if we want to take into consideration the use of steam plant, we shall have to start again from the curve MM′ showing the number of kilowatt-hours required to fill up the hollow in the curve AA′ (Fig. 1), and knowing the cost per kilowatt-hour generated by the steam plant we can calculate the annual cost of the steam power as a function of the total rated output of the plant. Using the same procedure as in the preceding case, we shall obtain a new position for the curve SS′, and a comparison of the two curves will show which is the better solution.

7. As a second example we can consider overhead-line construction. One of the hardest fights has been to convince people that power lines are just as much a question of engineering as a bridge, a railway, or a telpher line; and therefore engineering calculations can just as appropriately be applied to overhead lines.

I do not know why the construction of an overhead line has for so long been considered to be merely like stretching a rope between two poles for drying clothes. Fortunately, such times are over, and engineering—meaning thereby the art of doing what anybody can do, but doing it at the highest efficiency and at the lowest cost—is now applied also to overhead lines.

The mechanical problem of a power line consists, in general, in providing a suitable number of poles, structures or towers capable of supporting a certain number of conductors the sizes, characteristics and stresses of which are known.

We can use 20 supports per mile or we can use 10, but what number gives the greatest economy? Theory first, and experience subsequently, have shown that the length of the span does not affect the safety of a line—so much so, that even public authorities no longer insist on short spans for crossing roads. We must therefore be ready to adopt long spans if these prove to be advantageous. By lengthening the span, the number of supports decreases, but the supports must be higher owing to the greater sag of the wires, and heavier because the stress due to wind and snow on the conductors increases. The problem, therefore, becomes the determination of a minimum, which can be treated by the ordinary methods.

A very interesting investigation of this problem has been made by Mr. Carlo Fascetti of Leghorn.* The towers generally used for power transmission lines on the Continent are of the narrow-base type, the base almost always being square, and they are constructed entirely of standard angle-bar steel, except the arms, which may be of channel section (Fig. 3). The structure is in the form of a pyramid, having four angles connected by bracing lying in the faces of the pyramid.

By considering 12 different towers of this type built for various heights, spans and cross-sections of conductors, and calculated by engineers of different firms, Mr. Fascetti comes to the conclusion that for ordinary practice the relation between the weight of a support

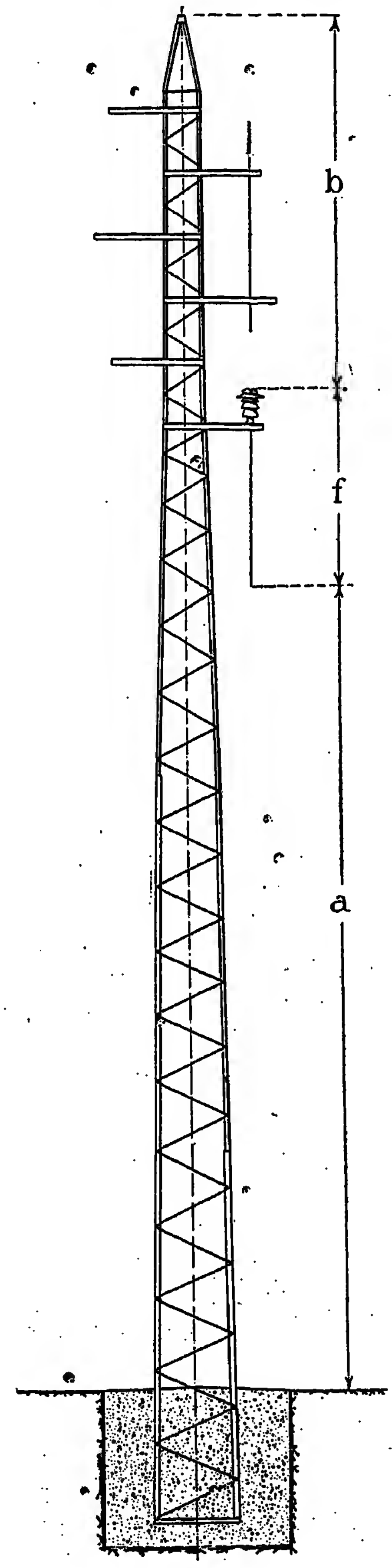

Fig. 3.

of this type and the moment of the acting stresses on the wires and the trellis structure itself, can be reduced to a simple expression of the form

$$P = 0{\cdot}025\,(nkdL + mH)H$$

where n is the number of conductors, d their diameter,

* *Elettrotecnica*, 1921, vol. 8, p. 486.

k a coefficient depending upon the effect of wind on round surfaces, L the span, m a constant depending on the pressure of wind on an iron structure, and H the height of the tower above the ground.

The above expression assumes that the pressure of the wind on the trellis-work is uniform and proportional to the height of the support. This assumption is justified by the fact that the angle of inclination of the columns is generally very small, and by the fact that the pressure on the arms carrying the insulators is neglected, this compensating for the difference in the surface of iron exposed to the wind.

Now a support of the type shown in Fig. 3 can be divided into three sections: the first, which I propose to call a, from the ground-level to the point to which the lowest wire is allowed to sag; the second, a length equal to the maximum sag f (which occurs with the maximum temperature and wind overload); and the third, the portion comprising the arms carrying the insulators, which I shall call b. The lowest section a and the top section b are independent of the sag, while the central one is a function of it. The height of the support above the ground can be written $H = (a + b) + f$, or, for simplicity, $H = h + f$. We know that the sag f is given as a function of the total stress G on the wire, the length L of the span, and the tension T per unit area of the conductor, by

$$f = \frac{L^2 G}{8T}$$

By making certain assumptions we can find the maximum value of f without making use of analytical processes, tables and curves. Let the maximum value be f_1 where

$$f_1 = \frac{L^2 G_1}{8T_1}$$

Then the weight of one support is given by

$$P = 0\cdot025\left[nkdL + m\left(h + \frac{L^2G_1}{8T_1}\right)\right]\left(h + \frac{L^2G_1}{8T_1}\right) \quad . \quad (1)$$

Now the number of towers per kilometre of line is equal to $1\,000/L$, where L is the span in metres, so that the total weight of iron per kilometre of line is $1\,000P/L = p$ say.

Equation (1) can then take the form

$$\frac{p}{0\cdot025} = nkdh + \frac{mh^2}{L} + nkd\frac{G_1}{8T_1}L^2 + m\frac{G_1^2}{64T_1^2}L^3 + 2mh\frac{G_1L}{8T_1} \quad . \quad (2)$$

in which the variables are p and L.

If we analyse the right-hand side of the equation into its components, we see that the first term $nkdh$ represents a horizontal straight line (1), the second term mh^2/L a hyperbola (2), the third term $nkdG_1L^2/8T_1$ a quadratic parabola (3), the fourth term $mG_1^2L^3/64T_1^2$ a cubic parabola (4), and the fifth term an inclined straight line (5).

Fig. 4 refers to an 80 000-volt line with three conductors, each 12·6 mm in diameter. The wind pressure is assumed to be 50 kg per metre of support, which may be taken to be an average value. Also let us assume the height above ground of the lowest point of the lower conductor to be 6 metres in warm weather, and the maximum stress on the wires to be 13 kg per mm^2.

If the above terms of Equation (2) are plotted in Fig. 4 the sum of their ordinates will give the total weight of iron in the towers per kilometre of line, corresponding to different values of the span. In order to reach a decision more quickly, we can consider the cost of the iron instead of its weight, and we then obtain curve (8) showing the cost of iron per kilometre of line.

We have now to add the cost of insulators and foundations.

8. The cost of insulators is constant for each support; hence if the cost of the insulators of one support is C, the cost per kilometre is $1\,000C/L$, and this is another parabola which has been plotted as (6) in Fig. 4. The relation between the cost of the foundations and the length of the span is not so simple. Opinions are very divided in regard to the method of calculating the foundations, and I shall therefore adopt the method which is most used.

The overturning moment of the foundation is given by the sum of the moments due to the wind stress on the wires and on the trellis structure.

$$\text{Thus } M = nkdLH + mH(\tfrac{1}{2}H)$$

This is a simplified formula, but is sufficiently accurate for our requirements. The resisting moment is given by

$$M_r = \tfrac{1}{2}Pc$$

where P is the weight of the foundations, and c the width of the block transversely to the line.

We can assume c to be proportional to H, so that we can put $c = BH$. Then, assuming that the resistance of the earth provides a factor of safety, we can write

$$\tfrac{1}{2}PcH = kndLH + \tfrac{1}{2}mH^2$$

or

$$\tfrac{1}{2}Pc = kndL + \tfrac{1}{2}mH$$

that is

$$P = \frac{2kndL}{BH} + \frac{m}{B}$$

The weight per kilometre of line is then

$$1\,000\frac{P}{L} = 1\,000\,\frac{2knd}{BH} + 1\,000\,\frac{m}{BL}$$

which is a hyperbola displaced from the axis of the abscissæ by the distance $2\,000knd/B$.

We can now determine the cost of the concrete, plot these different relations and sum up the ordinates of the various curves. The result is shown in the top curve in Fig. 4.

The minimum cost per kilometre of line is shown to be for a span of about 180 m, but the curve shows that good results can be obtained for any span between 150 m and 170 m, so that if there is any reason for departing slightly from the most economical span it can be done without much increase in cost.

In making the above calculations I have used a simple expression—which is only approximately correct—for the weight of the supports, but the method is fully justified by the result, which allows a certain latitude in the choice of the span.

9. I want to show, however, that as soon as the span is determined the structure itself can be calculated with much more accuracy.

In statics a tower of the type previously described could be considered to be a cantilever fixed at the base and subjected to a certain stress applied at a fixed distance from the ground. This stress, which is due to wind pressure acting on the conductors and on the tower itself, and also to components of the tension of the conductors, gives rise in the structure to a moment and a shear, which vary in accordance with the distance from the ground to the section of the tower under consideration.

If a definite section be considered, for instance the base section nearest to the ground, the values of the bending moment and shear on this section are completely determined, but we might design any number of structures capable of resisting the stress due to such a load, without the stress in the iron of the structure exceeding a particular value. Owing to their great length and small cross-section, it is important that the various parts of the structure should be capable of resisting buckling, and it is always necessary in this connection to employ a factor of safety.

As I have just mentioned, for a given factor of safety many different structures can be calculated capable of resisting the given bending moment and shear. These different structures are obtained by varying the dimensions of the individual parts, namely the width of the base, the area of the columns, the area of the bracings, and the angle of inclination of the bracings to the horizontal. How shall we choose between the various structures possible? This, again, is a question of determining a minimum value and is a new application of Kelvin's law. In fact if, for a given bending moment and shear, we increase the width of the base of the tower, the length of the bracings will increase and

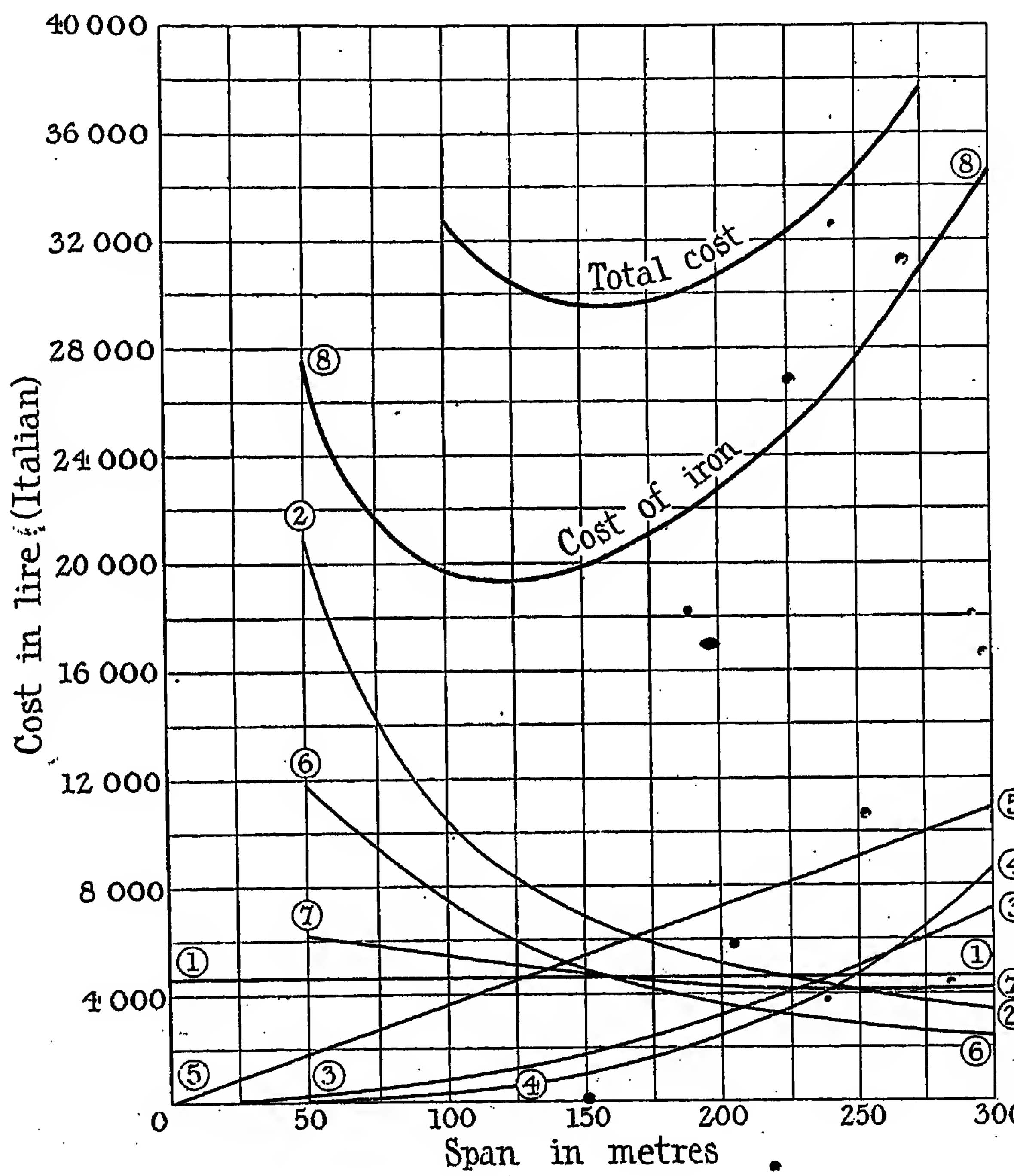

FIG. 4.

also their weight, the columns will be subjected to smaller stresses, and their cross-section will therefore decrease, so that we have a typical case of the sum of two quantities, one of which decreases when the other increases, and vice versa, so that the sum will reach a minimum under certain conditions.

It is unnecessary here to set out the calculation in detail, but Fig. 5 refers to a special case. The abscissæ show the width in centimetres of a square base, and the ordinates the weight in kilograms of the whole tower. It is interesting to notice the different manner in which the weight of the columns and the weight of the bracings vary, and the curve giving the total weight shows that it is not always true that a wider base results in a more economical structure. This answers a question which I am frequently asked: Why have the towers in connection with Italian transmission lines such narrow bases?

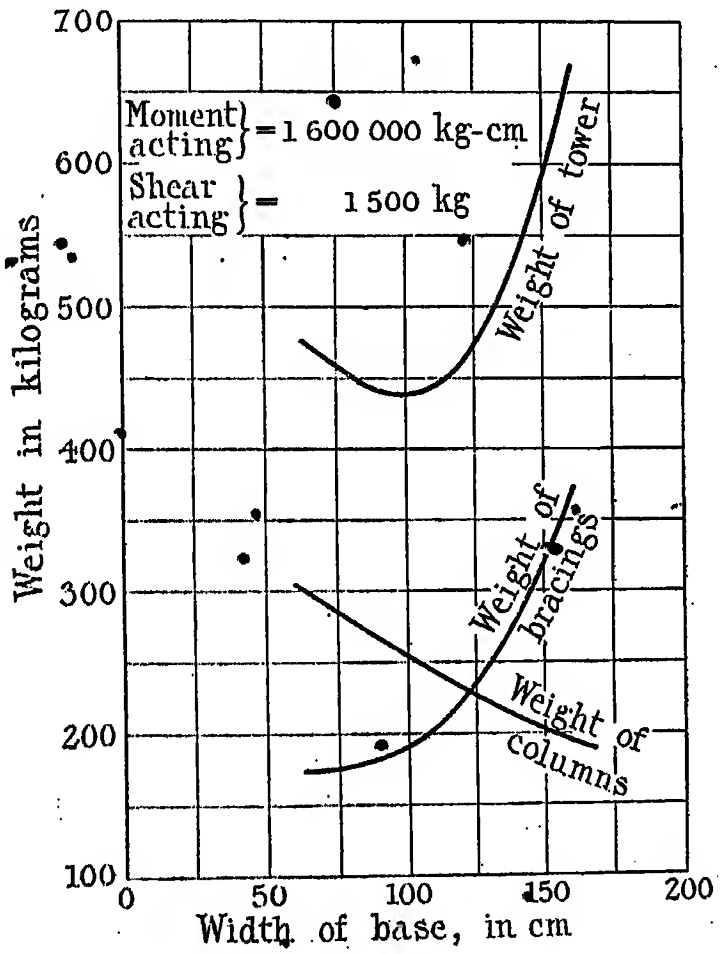

Fig. 5.

The principle explained above has been used in the preparation of tables and curves to allow us to calculate rapidly, when designing overhead lines, the dimensions of the towers to be used. The development of these methods is to be found in *Elettrotecnica*, 1921, vol. 8, pp. 220 and 454.

10. Let us now consider a problem which is more electrical than mechanical, namely, the choice of the most economical voltage for a transmission line. The voltage to be used for a transmission line has generally been settled either by the maximum permissible voltage or by the voltages of neighbouring installations. Years ago it was thought that the best result would always be obtained by using the highest voltage practicable, but when very high voltages were reached two new factors affected the solution. The first was the rapid rate of increase in the cost of insulators, towers, switchgear and transformers as the voltage was raised, and the second was the formation of a corona. As a result the simple law, which showed an economy in copper by raising the voltage indefinitely, conflicted with the general economic law, the extension of Kelvin's law; and also the problem of the most suitable voltage proved to be a question of determining the minimum cost.

Several attempts were made to solve the problem in a general way, and the most interesting work on this subject which I know is a paper by Mr. Claudio Castellani, who deals with the matter analytically.*

Owing to the corona effect, the problem is by no means simple. As long as the Joule effect alone is considered it is quite easy, but when the critical voltage is exceeded the diameter of the conductor must be made greater than its calculated size, in order to reduce the corona loss. The obvious solution would be to use a tubular copper conductor; but as a practical conductor of that type has not yet been economically produced the tube must be filled with copper. In other words, the area must be increased. Aluminium conductors can have a steel core, but this has more effect on the mechanical strength than on the carrying capacity of the conductor. The corona effect and the Joule effect are very different, the one depending on the voltage and the distance apart of the conductors, the other on the current.

Now, for a particular transmission the most economical voltage may be below or above the critical point corresponding to the conditions for the formation of a corona. Up to the present, lines have been so designed as to avoid the formation of a corona, and a definite conclusion has not yet been reached as to the desirability of allowing corona losses, although under special conditions the most economical transmission might necessitate a certain amount of corona loss. Up to the present we do not know how to settle this question.

The simplest way of dealing with the problem is first of all to ascertain the most suitable voltage without taking into account the possibility of a corona. Only if the calculated voltage and cross-section of the conductors for the assumed spacing should be above the critical point is it necessary to make a second calculation, taking into account the corona effect.

11. I do not propose here to describe the first calculation. That is based on the cost of the energy lost per annum due to the Joule effect, which is a function of the voltage and of the cross-section of the conductors, also on the cost per annum of the copper, which is a function of the cross-section of the conductors, and on the cost per annum of the insulation, supports, terminals, substations, etc., which is a function of the voltage. The result will be an expression containing as independent variables the voltage and the radius of the conductor, and the minimum cost can easily be determined. The graphic method of calculation presents no special difficulties.

The voltage and size so obtained disregard the possibility of a corona, leave out of consideration the spacing

* *Elettrotecnica*, 1921, vol. 8, p. 471.

of the wires, and make certain assumptions about the atmospheric pressure.

The spacing of conductors on high-tension lines is the result of experience, and I may say that the personal opinion of the designer also enters into the question. However, by collecting data from a large number of practical cases and plotting them on squared paper, I found that for pressures above 50 000 volts all the points lie close to a straight line passing through the origin. We are therefore justified in assuming a spacing proportional to the line voltage, the constant being about 3·14 (cm per kV).

12. Let us now suppose that in a particular case, taking into account the atmospheric pressure, the values of the voltage and radius calculated in the manner described above would involve conditions causing a corona loss. These values will no longer be applicable to the minimum conditions because a new loss has entered into the problem and was not allowed for in the previous calculation. It is necessary, therefore, to make new calculations.

In dealing with this problem it occurred to me, not only that a method could be devised for solving particular cases, but also that it was possible to obtain a general solution of problems of this nature. That is to say :—

(*a*) Is it possible to allow corona losses and find conditions for which the transmission will be more economical than if only Joule losses were considered ?

(*b*) For what conditions can this happen ?

(*c*) If for special reasons we want to allow a corona loss, how shall we determine the best condition ?

The corona losses for a three-phase line may be expressed as

$$w_c = Ar^2\left(\sqrt{\frac{r}{d}}\right)\left(\frac{V}{r} - B\log_e\frac{d}{r}\right)^2$$

where A = a function of the pressure of the air ;
r = radius of the conductors ;
d = spacing of the conductors ;
V = delta voltage of the line ;
$B = g_0 m_0 \delta$, and is a function of the pressure of the air.

Our calculations being confined to a determination of the most economical result throughout the year, we can determine in each case the mean atmospheric pressure throughout the year for the locality where the line has to be erected, so that we can now assume A and B to be constant.

We have shown that the spacing d between the conductors can be assumed to be proportional to the voltage, so that we are justified in writing $d = bV$. The expression for the corona losses then becomes

$$w_c = Ar^2\left(\sqrt{\frac{r}{bV}}\right)\left(\frac{V}{r} - B\log_e\frac{bV}{r}\right)^2$$

The sum of the corona and Joule losses will be

$$w = k\frac{W^2}{V^2r^2} + Ar^2\left(\sqrt{\frac{r}{bV}}\right)\left(\frac{V}{r} - B\log_e\frac{bV}{r}\right)^2 \quad . \quad (3)$$

This expression contains three variables, namely r, V and w, two of which are independent, so that it is a problem in three dimensions, and if we assume as independent variables r and V, the losses w are represented by points on a surface.

In considering the three dimensions let us set off the radius r of the conductors on the axis OX, the voltage V on OY, and the losses w on OZ.

Now we can easily find on the plane OX, OY, the positions where the corona effect occurs. The critical voltage corresponds to the conditions when the second term of Equation (3) vanishes, which occurs when

$$\frac{V}{r} - B\log_e\frac{bV}{r} = 0$$

It is easy to see that this equation determines the value of the ratio V/r, which we shall call m_0. The expression $V/r = m_0$ represents a straight line OM_0 passing through O, which I propose to call the critical line. All the points under the critical line OM_0 correspond to conditions which involve no corona loss, while corona loss arises for points above the line.

The solution of an expression of this form is not easy, but can be simplified by a proper choice of the variables. Instead of assuming as independent variables V and r, let us take V and the ratio $V/r = m$. The advantage of this assumption is that the expression in parentheses is constant for any particular value of m. By attributing different values to m, we proceed as if we explored the space by sectioning planes passing through the axis OZ (losses).

It should here be observed that all the solutions having the same value of m are similar in shape but of different dimensions, so that we can apply to this method all the properties of similar systems. For instance, when a calculation is made with a particular value of $V/r = m$, it is possible to find the minimum annual cost corresponding to the group of solutions which have in common this value of m. By a graphic method it is then possible to ascertain the group of solutions having the minimum value of m, that is, the minimum of the minima, and consequently the most advantageous point when the corona effect is taken into account, which is the desired solution. I should like to point out that, in endeavouring to determine this analytically, serious difficulties would be encountered, difficulties which are easily solved by graphic methods. It would take too long to discuss in detail in this Lecture this method of calculation, but it will be added as an Appendix.

13. I propose to confine my remarks to the method which I have just described. The two methods of calculation give two minima, one determined by neglecting corona losses, and the other taking such losses into account. These two minima have different dimensions.

Let us project the points representing these two minima on the plane OX, OY, and draw the straight line OM_0 which, as we saw, divides the plane into two parts—one in which corona losses occur, and one in which they do not. Each of these two minima, in order to have a real value and not be merely theoretical, must fall in the corresponding zone, the "corona" minimum above the line OM_0, and the "Joule" minimum below the line. The development of the method

shows that both these points can never have a real value, except under special conditions, when the points coincide, in which case they fall on the critical line.

A careful examination of the results brings us to the conclusion that in the normal conditions under which modern lines are constructed, and when the costs of energy, materials and labour are in their usual proportions, the majority of cases yield minima with Joule losses only. In order to fall in the zone of corona losses, the conditions must be rather unusual. The process enables us also to find the best conditions to be adopted when a corona effect is desired.

I do not propose to try the patience of members by discussing further examples, and I shall merely mention that Kelvin's law has been successfully applied to other hydraulic problems such as the determination of the best diameter of a penstock; to construction problems such as the determination of the best ratio between the iron and copper losses in a transformer; and to electric traction, in the determination of the most advantageous spacing of converter substations, and so on.

14. I do not know if I have succeeded in giving a sufficiently clear picture of the applications which Kelvin's law has received in all the fields of electrotechnics, and in convincing the members of the utility, in their everyday calculations, of the various developments of this law. However that may be, I can only say that the attempt to do so has given me the greatest pleasure, as I have regarded it as a tribute to the memory of the great master whom we have all come here this evening to honour.

My esteem for Kelvin dates from my college days when the magnitude of his work first impressed me so forcibly, and it was with deep emotion and respect that I approached him when, in the year 1906, as a representative of one of the kindred societies invited by this Institution, I came with other visitors to this country. On that occasion, during the receptions in Glasgow, I had the honour of presenting him, on behalf of the Associazione Elettrotecnica Italiana, with a facsimile of Leonardo's "Codex Atlanticus." I have ventured to mention this fact because it has often occurred to me since that such a gift had a special significance, as it brought together two great personalities who had from many points of view striking resemblances.

It is quite out of the question that the work of Leonardo could have had any influence on the development of Kelvin's ideas. During the latter's youth, Leonardo's scientific and philosophic works were almost unknown; his manuscripts, scattered, as they were, in different libraries, and written in a peculiar manner, which makes their reading very difficult, had been noticed only because of the beauty and originality of the sketches distributed throughout the text, to which sketches we owe the preservation of the manuscripts. Only after 1880 were they copied in legible characters and systematically studied, arousing general interest both for the depth and for the foresight of the ideas contained in them.

In reading Leonardo's notes, and having in mind Kelvin's personality, one is forcibly brought to compare these two men, born in different countries and separated in time by four centuries.

Silvanus Thompson, in his beautiful biography of Lord Kelvin, which formed the first of these Kelvin Lectures,* points out how Lord Kelvin always endeavoured to consider the physical meaning of any mathematical research, and shows the importance which he gave to the applications of science. "The life and soul of science is in its applications," he used to say. This tendency appears to have been somewhat original; and foreign students at that time who came to Great Britain to attend lectures in the universities, refer to it as a new feature in the methods of teaching due to Professor William Thomson.

In the forgotten notes of Leonardo, who lived when Aristotle's doctrines were still universally accepted, we find these words: "When you write on scientific matters be sure to add, after each proposition, the use you can make of it, if you don't want your science to be useless"; and, in a more poetic form, "Mechanics are the paradise of mathematical science, as by them we reach the mathematical fruit."

It will be remembered that Lord Kelvin used to say: "When you cannot measure or express in numbers what you are speaking about you have scarcely advanced to the stage of science." And Leonardo: "There is no certainty where one of the mathematical sciences cannot be applied." And further on, "No research can be called true science if it does not proceed through a mathematical demonstration."

I myself remember Lord Kelvin stating, in a private conversation in which the new electron theory was being discussed: "Marvellous things have been done in experimenting and calculating, but as to the physical meaning of all this we know nothing, and who can tell whether we shall ever know anything?" Leonardo did not hope for much more, as he wrote: "Although we know many of their effects, the knowledge of the intimate definition of the elements is forbidden to men." And many other resemblances between these two men could be quoted.

The coincidence of thought of these two scientists, widely separated in distance and in time, makes one thoughtful. It shows that the higher a scientist rises in intelligence, knowledge and power of research, the more he tends to reach a particular type. The identity of fundamental ideas and principles, found after the lapse of four centuries in men who had grown up quite independently and surrounded by radically different civilizations, culture and habits, shows that modern science, which embodies such ideas and principles, is proceeding along the right lines. The fact that Leonardo was born in Italy in the Middle Ages, and Kelvin in modern Britain, and that each was, on the whole, a genuine expression of his own race, shows once more, and perhaps under a new form, that science is the strongest international bond. From science will come the solution of the serious problem of how so many nationalities and races living and struggling on this little fragment of matter, wandering in the infinite, can exist peacefully one with another.

In conclusion I must express my indebtedness to

* *Journal I.E.E.*, 1908, vol. 41, p. 401.

Mr. Dino Nobili and Mr. Marco Semenza for their assistance in connection with the mathematical and engineering calculations in the Lecture.

APPENDIX.

In dealing with calculations in regard to the most economical voltage when corona losses are permissible, it is convenient to express by a formula the relation between the annual cost of the installation and the line voltage. By investigation of a number of practical cases it was found that the following relation can be adopted with fair accuracy:—

$$S_t = TV^2 + c \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where,

S_t = annual cost;
V = voltage, expressed in kilovolts;
T = sum of three terms, the first based on the cost of the insulators, the second on the cost of the towers, and the third on the cost of the terminal substations. The first two terms are proportional to the length of the line, and the third to the amount of power transmitted.

In this Lecture it has been stated that the spacing d between the conductors can be assumed to be

$$d = bV \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

A group of three conductors of a three-phase circuit is defined by the radius of each conductor and the spacing (which we shall assume to be uniform). Equation (5) allows us to substitute the voltage for the spacing.

The particular kind of system which is here considered is of the type for which $V/r = m$; that is to say, all systems having the same value of m are similar (see Fig. 6). For convenience, we shall assume the variables to be V and m. The annual cost of transmitting W kilowatts at a voltage V, when no corona loss occurs, is

$$S_j = J\frac{W^2}{V^2 r^2} + Rr^2 + TV^2 + c \quad . \quad . \quad . \quad (6)$$

where J is proportional to the length of the line, to the resistivity of the metal used, to the cost per kilowatt-hour, and to the number of hours of use, and inversely proportional to the square of the power factor; R is proportional to the length of the line, to the specific weight and cost of the metal used, and to the interest and sinking fund charges on the capital outlay on the conductors; and T is the same as in Equation (4).

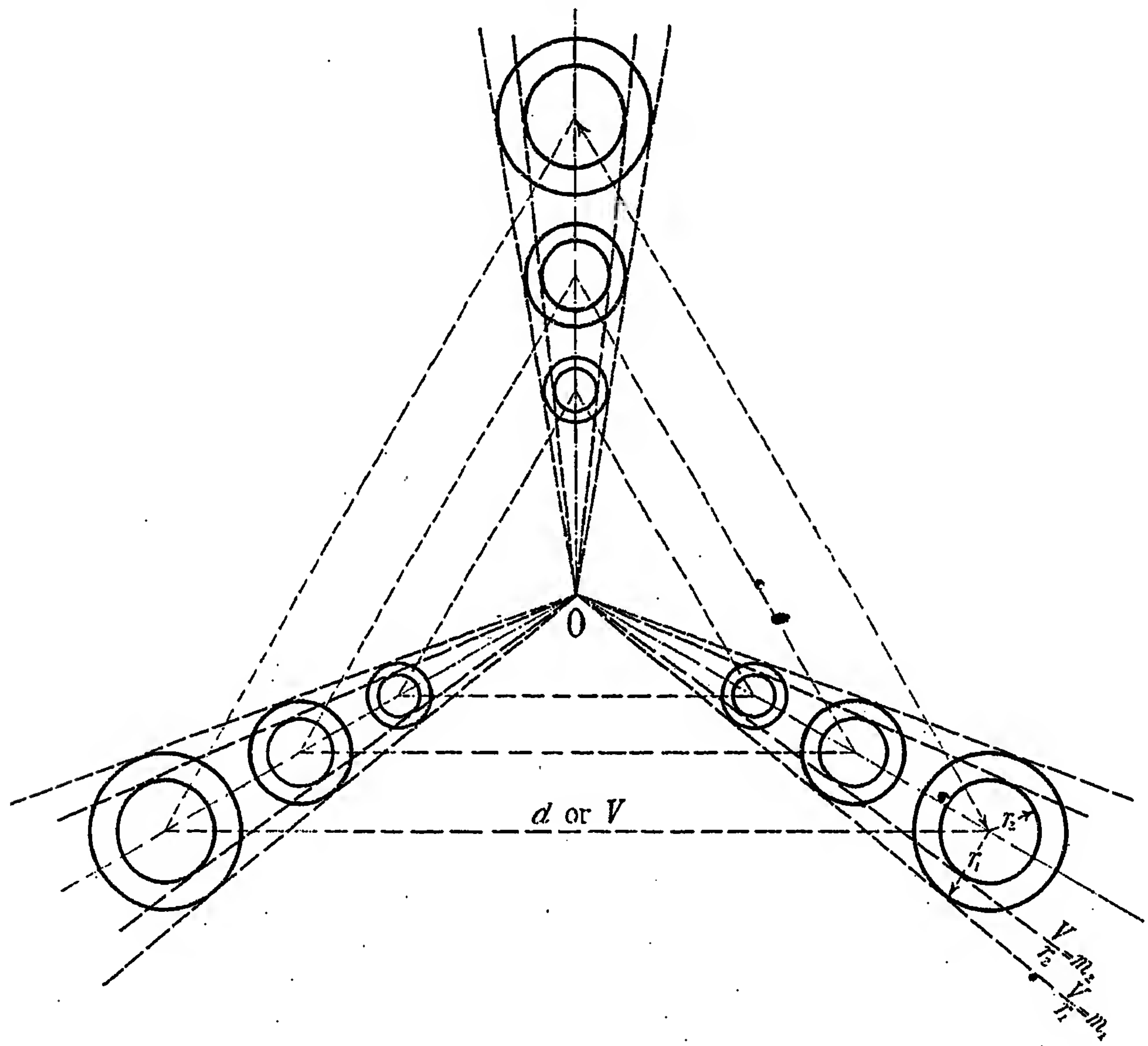

Fig. 6.

By substituting $m = V/r$ we obtain

$$S_j = J\frac{W^2m^2}{V^4} + \left(\frac{R}{m^2} + T\right)V^2 + c \quad . \quad . \quad (7)$$

Let us now assume for m a concrete value applicable to a particular system, the value of V corresponding to the minimum value of S_j. The annual cost of all systems having a common m is given by $\frac{dS_j}{dV} = 0$, that is by

$$-4J\frac{W^2m^2}{V^5} + 2\left(\frac{R}{m^2} + T\right)V = 0$$

which gives $$V = \sqrt[6]{\left(\frac{2Jm^4W^2}{R+Tm^2}\right)} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

and $$(S_j)_m = \frac{3}{\sqrt[3]{4}}\sqrt[3]{\left[JW^2\left(\frac{R}{m} + Tm\right)^2\right]} + c \quad . \quad (9)$$

What we are seeking is the minimum value of $(S_j)_m$ when m varies; that is, to find what value of m gives the minimum value of the various minima.

Inspection of Equation (9) shows that, in order to have $(S_j)_m$ a minimum, it is sufficient that $(R/m + Tm)$ should be a minimum; and, by making the derivative equal to zero, the condition for a minimum is $m = \sqrt{(R/T)}$, and the minimum itself, which we shall call $(S_j)_\mu$, is given by

$$(S_j)_\mu = 3\sqrt[3]{(JRTW^2)} + c$$

The corresponding cost per kilowatt-hour will be

$$(s_j)_\mu = \frac{3}{h}\sqrt[3]{\left(\frac{JRT}{W}\right)} + \frac{c}{hW} \quad . \quad . \quad . \quad (10)$$

The value of the resulting voltage is

$$V = \sqrt[6]{\left(\frac{JR}{T^2}W^2\right)} \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Let us now consider the expression $m = \sqrt{(R/T)}$.

From Peek's formula for corona losses it can easily be shown that the value of m corresponding to the critical voltage is

$$m_0 = B \log_e bm_0$$

This equation can easily be solved by using tables of hyperbolic sines and cosines.

If $\sqrt{(R/T)} < m_0$, no corona losses occur.

If $\sqrt{(R/T)} > 0$, there will be corona losses.

Corona losses are expressed by

$$w_c = Ar^2\frac{(m - B\log_e bm)^2}{\sqrt{m}}$$
$$= \frac{A(m - B\log_e bm)^2}{\sqrt{m}} \cdot \frac{V^2}{m^2}$$

The cost of the energy loss by corona effect is given by

$$S_c = ALhc_k\frac{(m - B\log_e bm)^2}{\sqrt{m}} \cdot \frac{V^2}{m^2}$$

where L = length of the line;
h = number of hours per annum during which the voltage is on the line;
c_k = cost per kilowatt-hour.

Let us put $$\frac{(m - B\log_e bm)^2}{\sqrt{m}} = Q$$

then $$S_c = ALhc_kQ\frac{V^2}{m^2}.$$

Adding this cost to that of the conductor insulation and of the supports and terminal substations, we can express the total cost as

$$S_{jc} = \frac{JW^2m^2}{V^4} + \left(\frac{R + CQ}{m^2} + T\right)V^2 + c$$

where $C = ALhc_k$.

We could proceed to determine the minimum value of this function by the ordinary methods, but it is simpler to proceed in two steps, the first being the determination of the minimum value for a group of systems having the same value of m, which is therefore constant. In this case we can use the preceding formulæ, substituting $(R + CQ)$ for R.

The expressions for S and V become

$$S = \frac{3}{h\sqrt[3]{4}}\left\{\sqrt[3]{\left[\frac{J}{W}\left(\frac{R}{m} + mT + \frac{CQ}{m}\right)^2\right]} + \frac{c}{hW}\right\}$$

and $$V = \sqrt[6]{\left(\frac{2Jm^4W^2}{R + CQ + Tm^2}\right)}$$

The smallest of the minimum values should be calculated by equating to zero the first derivative of the equation

$$\frac{R}{m} + Tm + \frac{CQ}{m} = \Phi$$

The process would, however, prove very long and complicated. It is easier to plot the curve of Φ as a function of m. The ordinates of this curve are the sum of the ordinates of the hyperbola $(R/m + mT)$, which corresponds to the losses when corona effect is absent, and of the ordinates of the expression CQ/m, which is Peek's equation divided by m.

This equation can assume the following form

$$F = C\frac{(m - B\log_e bm)^2}{m\sqrt{m}}$$

This function, in the region in which it has a real meaning, namely $(d > 2r)$, has only one minimum, and this is zero. The sum of the ordinates of these curves gives us the curve of Φ, and the minimum of this quantity establishes the conditions of maximum economy for the transmission.

The following remarks can be made in conclusion:

(1) It is impossible to calculate the most economical voltage without taking into consideration at least two independent variables, and the most convenient are V and $V/r (= m)$.

(2) The simplest graphic representation is by projecting on a plane the intersection of a number of parallel planes and the surface considered.

(3) The surface representing the case in which no corona effect occurs is different from that representing the surface for which corona losses occur, but the

intersection of these two surfaces is contained in a plane perpendicular to the plane of reference, the projection of which on this is the straight line OM_0 (see Fig. 7).

(4) Each minimum, in order to have a physical meaning, must fall in the region applicable to the conditions, otherwise the solution is merely mathematical.

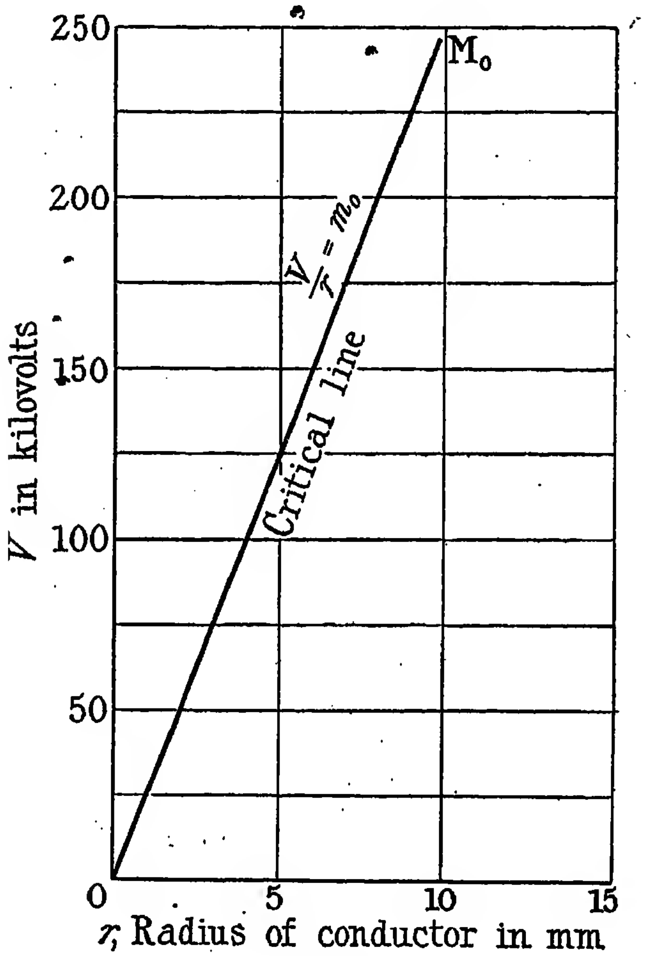

FIG. 7.

(5) In every case in which the minimum falls in a region in which corona losses occur it will be interesting to examine the effects of a change in the relation between V and d with a view to avoiding corona losses.

Near the beginning of the Appendix it was stated that the different costs can, for convenience, be expressed by simple relations. Such relations have been determined by plotting a number of practical values and drawing a smooth curve as near as possible to the figure which results if such points are connected by straight lines. By making use of present costs I have obtained the following expressions:

$$
\begin{aligned}
J &= 0\cdot008455\ LC_w h \\
R &= 80\cdot12 pkL \\
T &= 0\cdot1503\ L + 0\cdot000148\ W + 3\cdot18 \\
c &= 608\ L + 4\cdot32\ W + 28\ 800
\end{aligned}
$$

where L = length of the line in kilometres;
C_w = cost per kilowatt-hour delivered to the line;
h = number of hours during which current is used per annum;
p = cost of copper per kilogram; and
k = interest and sinking fund charges on the copper.

The resistivity of copper has been assumed to be 1·7, and its specific gravity 8·5.

We have seen that in the formula $d = bV$ the practical value of b is 3·14 when r is expressed in centimetres.

Example. 30 000 kW has to be transmitted a distance of 120 km by three-phase current.

Let us assume:

power factor = 0·8;
C_w (cost of kilowatt-hour delivered to line) = 0·10 lire;
p (cost of copper) = 9 lire per kilogram;
k (interest charges, etc.) = 8 per cent;
h (hours of utilization) = 4 000.

We have

$$
J = 405\cdot84 \qquad R = 6\ 923
$$
$$
T = 25\cdot66 \qquad c = 231\ 360
$$

Inserting these values in the equation $m = \sqrt{(R/T)}$, we find $m = 16\cdot43$.

We can now find the critical value of m_0, which is $m_0 = 24\cdot25$. In order that the corona effect may be present we ought to have

$$
R/T \geq m_0^2, \text{ that is } R/T \geq 588
$$

But $R/T = 269\cdot8$, and therefore the minimum falls in the region where no corona effect occurs.

By applying the preceding formulæ we find the most economical voltage, $V = 128$ kilovolts.

The cost of the transmission, $s_j = 0\cdot0119 \sim 0\cdot012$.

The radius of the conductor, $r = 8\cdot95$ mm; and the distance between conductors, $d = 402$ cm.

COUPLING BETWEEN TWO OSCILLATORY CIRCUITS, WITH SOME APPLICATIONS.*

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(Paper first received 10th March, and in final form 7th July, 1924.)

SUMMARY.

(1) *Introduction.*

The different methods of coupling two oscillatory circuits are conveniently classified as follows:—

(i) Indirect coupling through a field of force common to both oscillatory circuits.
(ii) Direct coupling through an impedance common to both circuits.
(iii) Direct coupling through an impedance not included in either oscillatory circuit.

(2) *The Physics of Tuned Coupled Circuits.*

An easy method of obtaining the values of the two resonant frequencies for each system is described. The method is based upon current considerations and is applicable to the case when the two circuits are tuned to the same frequency. The method is illustrated by applying it to a type of inductive coupling.

(3) *The Frequency Variations.*

The properties peculiar to the two resonant frequencies for each type of coupled circuit are discussed, and coupling units are described by which the resonant frequencies of the directly coupled circuits may be made continuously variable.

(4) *Applications.*

These coupling units are applied to an aerial circuit in such a manner that each resonant frequency of the system can be varied independently of the other, over any desired range of frequency. By this method of dual reception each wave-length is properly tuned and one aerial only is employed.

Finally, the coupling units are applied to the intervalve system of a high-frequency amplifier, thereby enabling the amplifier to be readily tuned to any frequency and to amplify two signals independently and simultaneously.

(1) INTRODUCTION.

Various technical publications have dealt with several forms of coupling between wireless oscillatory circuits. The various possible methods may be conveniently divided into three classes:—

Class (i). Indirect coupling through a field of force common to both oscillatory circuits.

Class (ii). Direct coupling through an impedance common to both oscillatory circuits.

Class (iii). Direct coupling through an impedance not included in either circuit.

These classes are depicted in Fig. 1, resistance coupling being neglected. In what follows, resistances in the oscillatory circuits will be neglected, as, unless they are very large, they will not affect the resonant frequencies of the systems.

Circuits coupled as in Figs. 1 (*a*), 1(*c*), 1 (*d*), and 1(*f*) have been treated from some aspects in most standard textbooks, whilst the forms of coupling depicted in Figs. 1 (*b*) and 1(*e*) have been added for completeness. Fig. 1 (*b*) is intended to represent two circuits coupled by placing one condenser in the field of force set up by the other.

In every case the coupled system has a minimum value of impedance for two values of ω, where ω is

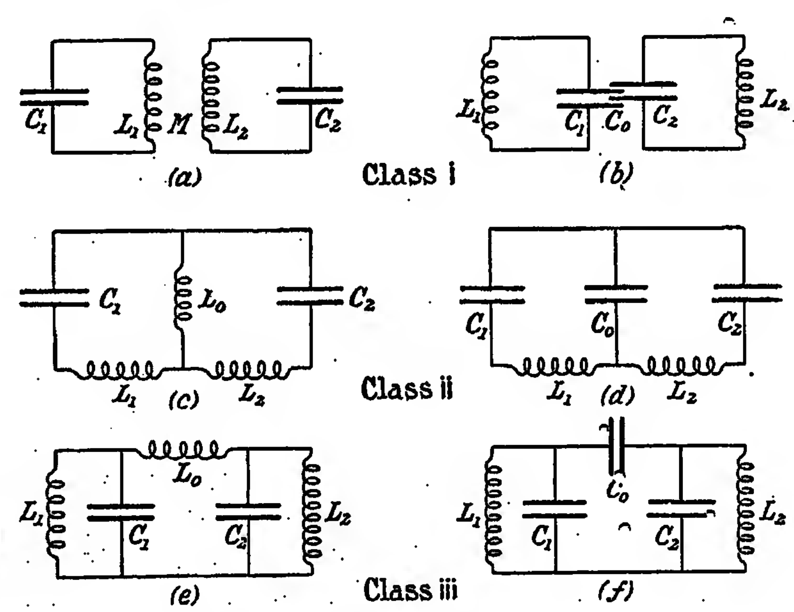

FIG. 1.

equal to 2π times the frequency. The variations in the resonant frequencies with variations in the coupling unit depend on the conditions of tuning. For the simplest and most usual relationship between the LC products the resulting resonant frequencies are collected in Table 1, where the symbols have the significance indicated in Fig. 1.

(2) THE PHYSICS OF TUNED COUPLED CIRCUITS.

Many of these results have been published elsewhere and all of them can be obtained by the usual analytical methods. There is, however, a simpler method of obtaining the more important results for which the condition $L_1C_1 = L_2C_2 = LC$ is fulfilled. With this particular condition the two resonant frequencies occur when the currents in the separate circuits are, at any instant, circulating in the same or in opposite directions respectively. The system, as a whole, presents alternative relative directions to the currents, and the

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direction of rotation depends upon the particular frequency of the incident energy. This will be illustrated with reference to Class (iii) e which has not been dealt with hitherto.

Experiments carried out with this form of circuit, in which vacuum thermo-junctions and galvanometers had been inserted, revealed the fact that when incident energy was of the frequency $\omega_1/2\pi$ [where $\omega_1 = 1/\sqrt{(L_1C_1)}$] whole system. The impedance of L_0 is negligible compared with infinity, and its value will also have no effect on the resonant frequency. Thus the resonant frequency of the system with this particular current distribution will be the same as that of either of the circuits separately. Such a current distribution will thus account for the frequency $\omega_1/2\pi$. In practice the current in the coupling inductance is not quite zero

TABLE I.

Circuit	ω_1	ω_2	Conditions
(i) a	$1\Big/\sqrt{\left[LC\left\{1+\frac{M}{\sqrt{(L_1L_2)}}\right\}\right]}$	$1\Big/\sqrt{\left[LC\left\{1-\frac{M}{\sqrt{(L_1L_2)}}\right\}\right]}$	$L_1C_1=L_2C_2=LC$
(i) b	$1\Big/\sqrt{\left[LC\left\{1+\frac{C_0}{\sqrt{(C_1C_2)}}\right\}\right]}$	$1\Big/\sqrt{\left[LC\left\{1-\frac{C_0}{\sqrt{(C_1C_2)}}\right\}\right]}$	$L_1C_1=L_2C_2=LC$
(ii) c	$1\Big/\sqrt{\left[LC\left\{1+\frac{L_0}{\sqrt{[(L_1+L_0)(L_2+L_0)]}}\right\}\right]}$	$1\Big/\sqrt{\left[LC\left\{1-\frac{L_0}{\sqrt{[(L_1+L_0)(L_2+L_0)]}}\right\}\right]}$	$(L_1+L_0)C_1=(L_2+L_0)C_2=LC$
(ii) c	$1/\sqrt{(LC)}$	$1/\sqrt{\{LC+L_0(C_1+C_2)\}}$	$L_1C_1=L_2C_2=LC$
(ii) d	$1\Big/\sqrt{\left[LC\left\{1+\sqrt{\frac{C_1C_2}{(C_1+C_0)(C_2+C_0)}}\right\}\right]}$	$1\Big/\sqrt{\left[LC\left\{1-\sqrt{\frac{C_1C_2}{(C_1+C_0)(C_2+C_0)}}\right\}\right]}$	$L_1\frac{C_1C_0}{C_1+C_0}=L_2\frac{C_2C_0}{C_2+C_0}=LC$
(ii) d	$1/\sqrt{(LC)}$	$1\Big/\sqrt{\left\{LC\left(\frac{C_0}{C_1+C_2+C_0}\right)\right\}}$	$L_1C_1=L_2C_2=LC$
(iii) e	$1\Big/\sqrt{\left[LC\left\{1+\sqrt{\frac{L_1L_2}{(L_1+L_0)(L_2+L_0)}}\right\}\right]}$	$1\Big/\sqrt{\left[LC\left\{1-\sqrt{\frac{L_1L_2}{(L_1+L_0)(L_2+L_0)}}\right\}\right]}$	$\frac{L_1L_0}{L_1+L_0}C_1=\frac{L_2L_0}{L_2+L_0}C_2=LC$
(iii) e	$1/\sqrt{(LC)}$	$1\Big/\sqrt{\left\{LC\left(\frac{L_0}{L_1+L_2+L_0}\right)\right\}}$	$L_1C_1=L_2C_2=LC$
(iii) f	$1\Big/\sqrt{\left[LC\left\{1+\frac{C_0}{\sqrt{[(C_1+C_0)(C_2+C_0)]}}\right\}\right]}$	$1\Big/\sqrt{\left[LC\left\{1-\frac{C_0}{\sqrt{[(C_1+C_0)(C_2+C_0)]}}\right\}\right]}$	$L_1(C_1+C_0)=L_2(C_2+C_0)=LC$
(iii) f	$1/\sqrt{(LC)}$	$1\Big/\sqrt{\left\{LC\left(1+\frac{C_0}{C_1}+\frac{C_0}{C_2}\right)\right\}}$	$L_1C_1=L_2C_2=LC$

no current was measurable in the coupling inductance L_0; whilst when the incident energy was at the frequency $\omega_2/2\pi$ $\left[\text{where } \omega_2 = 1\Big/\sqrt{\left(LC\frac{L_0}{L_1+L_2+L_0}\right)}\right]$ the current in L_0 was approximately equal to the difference of the currents in L_2 and in C_2. The interpretation of these results is as follows. At the frequency $\omega_1/2\pi$ the currents in the two circuits were oscillating in opposite directions at any one instant, whilst at the frequency $\omega_2/2\pi$ the currents were oscillating in the same direction at any instant. This is shown in Fig. 2(a) by the dotted and full-line arrows respectively.

When currents flow in the directions indicated by the dotted arrows they pass downwards through the condensers and upwards through the inductances simultaneously. Then the two points A and B will be at the same potential and consequently no current will flow in the coupling inductance. The circuits will act towards each other as rejector circuits and provide infinite impedance paths parallel to their inductance or capacity. The presence of this path, therefore, will not affect the resonant frequency of either circuit or of the owing to the ohmic losses in the circuit L_2C_2, and consequently a small power current flows in L_0 to compensate for this wastage. This is equivalent to saying that there will be a small potential difference between the points A and B.

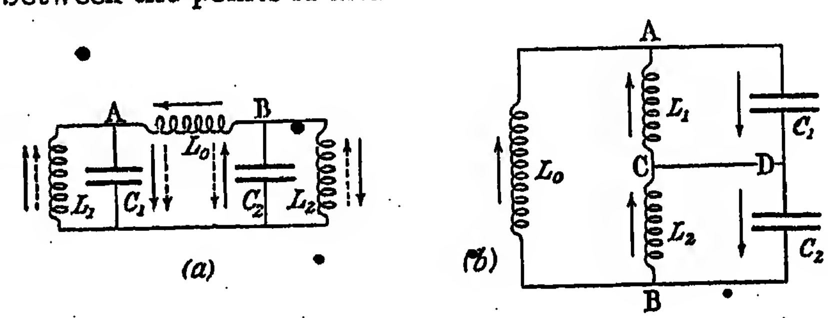

FIG. 2.

The second resonant frequency arises when the currents flow in the directions indicated by the full-line arrows. In this case the currents in C_1 and C_2 are, at any instant, flowing in opposite directions and the points A and B will be 180° out of phase, with a consequent flow of current in the coupling inductance.

Suppose the circuit be re-drawn as in Fig. 2 (*b*). Then, since $L_1C_1 = L_2C_2$,

$$(1/\omega C_1)/(1/\omega C_1 + 1/\omega C_2) = \omega L_1/(\omega L_1 + \omega L_2)$$

and therefore the potential fall from A to C is the same as that from A to D. Hence C and D will be at the same potential and no current will flow along CD. The frequency $\omega_2/2\pi$ will therefore be the same as the frequency of a simple oscillating circuit in which the equivalent inductance L' is equal to the value of L_0 in parallel with L_1 and L_2 in series, that is :—

$$L' = \frac{L_0(L_1 + L_2)}{L_1 + L_2 + L_0}$$

The equivalent capacity C' will be given by C_1 and C_2 in series, that is :—

$$C' = \frac{C_1C_2}{C_1 + C_2}$$

Hence $\omega_2 = 1/\sqrt{(L'C')}$

$$= 1\Big/\sqrt{\left[\frac{L_0(L_1 + L_2)}{L_1 + L_2 + L_0} \cdot \frac{C_1C_2}{C_1 + C_2}\right]}$$

or $$1\Big/\sqrt{\left(\frac{L_1C_1C_2 + L_2C_2C_1}{C_1 + C_2} \cdot \frac{L_0}{L_1 + L_2 + L_0}\right)}$$

Since $L_1C_1 = L_2C_2 = LC$, this reduces to

$$\omega_2 = 1\Big/\sqrt{\left[LC\left(\frac{L_0}{L_1 + L_2 + L_0}\right)\right]}$$

This value is identical with that obtained by equating the total circuit impedance to zero and solving the resulting equation for ω, and hence justifies the interpretation of the experimental results stated above.

The method is quite general for those cases where it is possible to keep the circuits in tune, whilst varying the coupling unit.

(3) The Frequency Variations.

An examination of the results collected in the table reveals the fact that with class (i) both the resonant frequencies are equally dependent on the value of the coupling unit. This is necessarily the case because the value of the product of the inductance and capacity of either circuit is dependent on the value of the coupling, and vice versa. With class (ii) the normal condition is for one frequency to be fixed, or independent of the value of the coupling unit. The other frequency increases from zero to $1/[2\pi\sqrt{(LC)}]$ as the coupling inductance decreases from infinity to zero, whilst the frequency value increases from $1/[2\pi\sqrt{(LC)}]$ to infinity as the coupling capacity decreases from infinity to zero. Thus a coupling unit comprising both inductance and capacity will enable the frequency $\omega_2/2\pi$ to be varied at will over any range of frequency.

The other solutions for class (ii) are only obtained when special precautions are taken to fulfil the required conditions. In other words, the value of one of the circuit components must be continually varied as the coupling unit is varied. This requirement prohibits any convenient practical application of the result.

In class (iii) one frequency ($\omega_1/2\pi$) is again fixed or independent of the coupling unit, whilst the other depends upon it. This second frequency ($\omega_2/2\pi$) increases from zero to $1/[2\pi\sqrt{(LC)}]$ as the capacity coupling decreases from infinity to zero. This is comparable with the effect of inductance coupling in class (ii). The frequency increases from $1/[2\pi\sqrt{(LC)}]$ to infinity as the inductance decreases from infinity to zero; a result obtained by decreasing the capacity in class (ii). Thus with a coupling unit including both inductance and capacity, $\omega_2/2\pi$ for this type of coupling can also be varied to any extent required.

(4) Applications.

(*a*) *A method of dual reception.*—The presence of two frequency values for which the impedance of two coupled circuits is a minimum suggests the possibility of receiving or sending simultaneously two signals at these particular frequencies. The simplest method would be to utilize an aerial with suitable tuning capacity and inductance as one oscillatory circuit and to couple them by a combined condenser and inductance coupling unit to a second oscillatory circuit as in classes (ii) or (iii), where L_1C_1 would be replaced by the aerial circuit.

This method, however, has the obvious disadvantage that only one frequency ($\omega_2/2\pi$) can be varied without upsetting the other frequency ($\omega_1/2\pi$). The difficulty can be overcome by a somewhat complicated gearing arrangement between the three condensers and inductances.

A better method is that indicated in Fig. 3, which enables each operator to receive signals over the whole

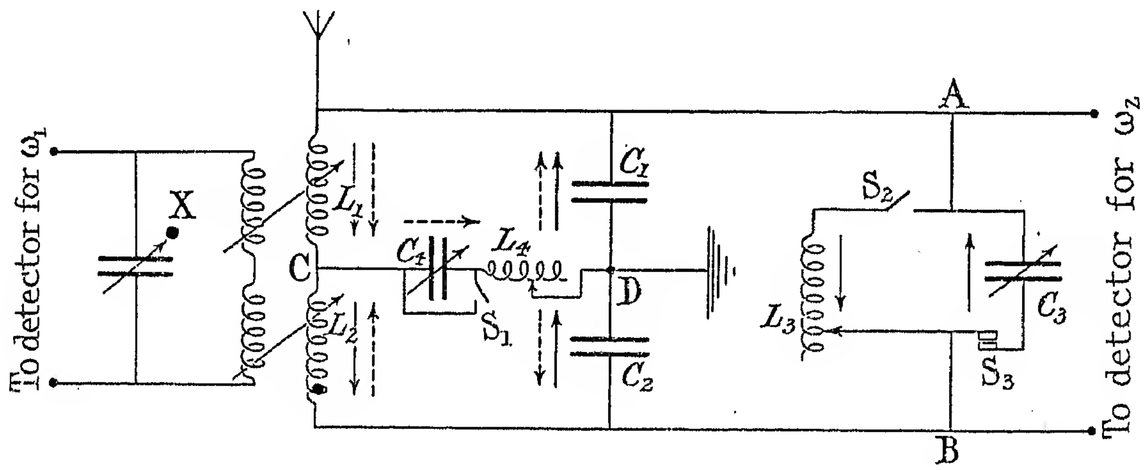

Fig. 3.

range of possible frequencies. This arrangement requires only one aerial and combines all four forms of coupling shown in Figs. 1 (c), 1 (d), 1 (e) and 1 (f). The method of operation can be most readily understood by a consideration of the arrows indicating instantaneous current directions. When currents at the frequency $\omega_1/2\pi$ are induced in the system the directions at any instant are indicated by the dotted arrows. The points A and B are at the same potential (since $L_1C_1 = L_2C_2$) and consequently C_3 (or L_3) does not affect the resonance frequency of currents taking these paths. When the currents flow in the direction of the full-line arrows, their frequency being $\omega_2/2\pi$ there is no difference of potential between C and D, and hence $\omega_1/2\pi$ can be varied by manipulating C_4 (or L_4) without affecting $\omega_2/2\pi$. Each operator will therefore control one coupling unit, thereby varying, in whatever manner he may desire, one only of the two resonance frequencies of the system. Each resulting frequency will be entirely independent of the frequency determined by the other control unit.

It will be noticed that L_3 and C_3 are used in parallel to vary $\omega_2/2\pi$. This is desirable because at the frequency $\omega_2/2\pi$ the path through L_3 is in parallel with that through L_1 and L_2 (Fig. 3, full-line arrows), and to bring $\omega_2/2\pi$ from higher values to $1/[2\pi\sqrt{(L_1C_1)}]$, L_3 must approach infinity. C_3 is in parallel with C_1 and C_2, and to bring $\omega_2/2\pi$ from lower values to $1/[2\pi\sqrt{(L_1C_1)}]$, C_3 must approach zero, i.e. approach infinite impedance. L_3 and C_3 in parallel fulfil these requirements if tuned to $1/[2\pi\sqrt{(L_1C_1)}]$. The variation with frequency of the impedance of such a circuit is shown in Fig. 4 (a).

For a similar reason L_4 and C_4 are used in series to bring $\omega_1/2\pi$ nearer to $1/[2\pi\sqrt{(L_1C_1)}]$. Considering the distribution of currents for $\omega_1/2\pi$ (Fig. 3, dotted arrows) it will be seen that for $\omega_1/2\pi$ to approach $1/[2\pi\sqrt{(L_1C_1)}]$ the combined impedance of L_4 and C_4 must approach zero. This is accomplished by putting them in series, when zero impedance is obtained if $L_1C_1 = L_4C_4$. The variation of impedance with frequency in this case is shown in Fig. 4 (b).

In the practical form it will be necessary to vary the condenser C_1 to tune the aerial circuit to the same value as L_2C_2. L_3 and C_3 will be provided with open-circuiting switches (S_2 and S_3) operating automatically (not shown in detail in Fig. 3) so that as each or either decreases appreciably from its maximum impedance value the other is cut out. C_3 only is used when $\omega_2/2\pi$ is less than $1/[2\pi\sqrt{(L_1C_1)}]$, and L_3 only is required for frequencies greater than $1/[2\pi\sqrt{(L_1C_1)}]$. L_4 and C_4 can be so constructed that they short-circuit themselves, L_4 when it reaches its minimum value and C_4 when it reaches its maximum value (switch S_1 in Fig. 3).

Signals at frequency $\omega_2/2\pi$ can be detected by connecting the detector to AB (Fig. 3). These points are always at a potential 180° out of phase for $\omega_2/2\pi$ and in phase for $\omega_1/2\pi$, so that signals of this latter frequency will not be detected unless strong enough to give a fall of potential due to resistance differences.

Signals at frequency $\omega_2/2\pi$ can be detected across C and D (Fig. 3) except in the special case when $L_1C_1 = L_4C_4$, when the resonance frequency is such that the impedance between C and D is zero and the signal strength is consequently zero. This can be overcome in practice by using a circuit X (Fig. 3) tuned to $\omega_1/2\pi$ and loosely coupled to L_1 and L_2 in such a manner that the induced E.M.F.'s due to currents at the frequency $\omega_1/2\pi$ add up in the loose-coupled circuit. With such an arrangement currents of frequency $\omega_2/2\pi$ will induce opposing E.M.F.'s in the loose-coupled circuit (see arrows in Fig. 3). $\omega_2/2\pi$ will be unaffected provided that the two couplings of the loose-coupled circuit remain equal.

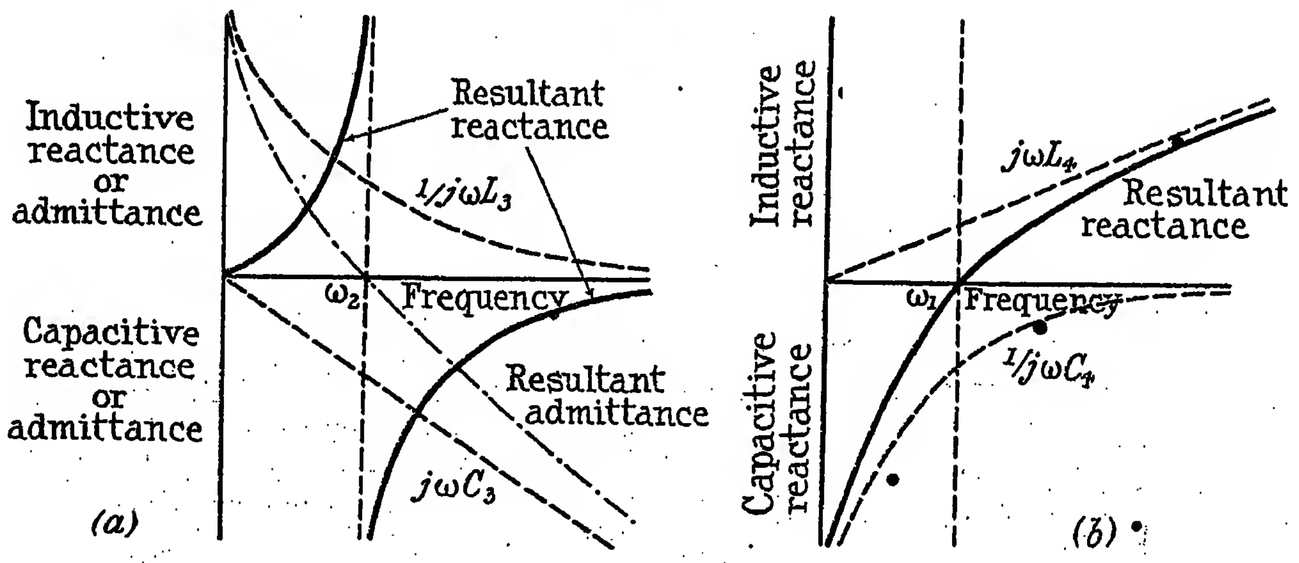

FIG. 4.

A similar loose-coupler can be used for signals at $\omega_2/2\pi$, but this method is not as good as that already indicated because for the higher values of $\omega_2/2\pi$, when L_3 is small compared with $L_1 + L_2$, the current through L_1 and L_2 will be small compared with that through L_3.

A receiving circuit designed on these lines was found to function in this manner and to be capable of receiving simultaneously and independently two signals of any required frequencies. Resonance curves were taken which showed the two resonant frequencies to be quite independent. The decrement of either path was not affected by the presence of the other, for the curves indicated decrement values of the same magnitude as for simple LC circuits including similar components. These resonance curves were obtained by inserting vacuum thermo-junctions in the various branches of

the circuit, and thereby obtaining direct-current measurements. The source of energy was a valve generator controlled to give constant current in the exciting circuit to which the circuit under test was coupled by a fixed mutual inductance. By this method the E.M.F. induced in the test circuit varied directly

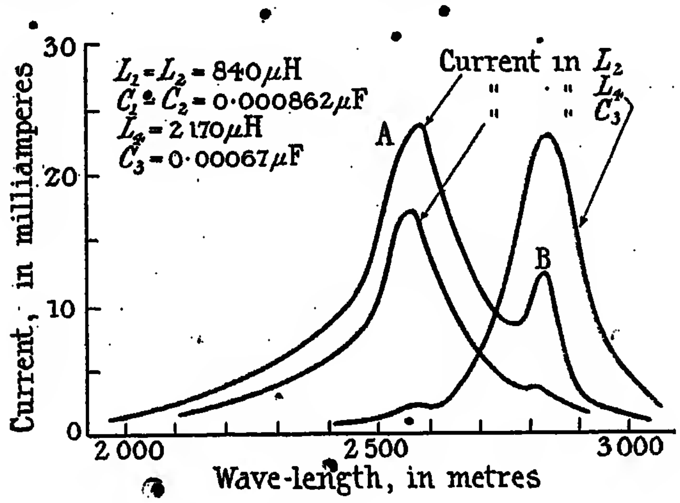

FIG. 5.

as the frequency. Consequently the height of the resonance peak B (Fig. 5) is less than that of A.

Apart from this, the variation of the height is in accordance with the resistance variation in the respective paths taken by the currents. Some typical curves are given in Fig. 5 from which it can be seen that the current at a frequency of $v/2$ 850 in the coupling inductance L_4 is quite independent of the current at a frequency $v/2$ 550 in the coupling capacity C_3 (where v is the velocity of light).

(b) *An intervalve system for high-frequency amplifier.*— A common type of high-frequency amplifier is that shown in Fig. 6, except that the coupling unit C_0 is usually a fixed condenser of large value and the circuit L_3C_3 is replaced by a third valve.

This tuned choke intervalve system may be compared with two oscillatory circuits coupled as in Fig. 1 (*f*). The first circuit comprises the anode choke L_A and the valve capacity (anode to filament) C_A, whilst the second circuit consists of the grid choke L_G and the valve capacity (grid to filament) C_G. To obtain maximum amplification these two circuits are both tuned to the frequency of the signals it is desired to amplify. Neglecting ohmic resistances the paths from anode and grid to earth are of infinite impedance at this frequency, while the anode and grid circuits themselves have zero reactance to currents of this particular frequency which circulate in them. As this infinite impedance is attained without the use of high resistances, the system is particularly efficient. It suffers, however, from the disadvantage that it will only amplify effectively at the one frequency, unless some means is provided for re-tuning the anode and grid circuits to the new frequency.

The foregoing discussion on this form of coupled circuit has shown that there is another frequency at which the system offers zero reactance to currents in L_A and L_G, which frequency depends on the value of the coupling condenser.

At this frequency, which has been called $\omega_2/2\pi$, the potentials of the anode of any valve and the grid of the following valve are 180° out of phase. Hence the grid will again be subjected to large potential variations. If C_0 is made variable (as shown in Fig. 6) this frequency can be varied and the system made to amplify efficiently for any wave-length within the range determined by the values of the component inductances and capacities. If all the coupling condensers are geared together as shown, the process of tuning the whole amplifier is reduced to one operation.

Besides this simplification of control, the intervalve system has the additional advantage that a step-up in voltage is possible, making the variations of grid potential greater than the variations of anode potential. This can be seen from the fact that the currents in L_A and L_G for the frequency $\omega_2/2\pi$ are equal (see page 897), and hence if $L_A < L_G$ there will be a voltage step-up given by L_G/L_A. In general, since the effective value of the valve grid-filament capacity (C_G) is smaller than the anode-filament capacity (C_A), this step-up is assured.

Normally the potential ratio in this intervalve system is unity, and the large coupling condenser merely allows the grid potential to vary equally and in phase with the anode potential of the preceding valve. The value

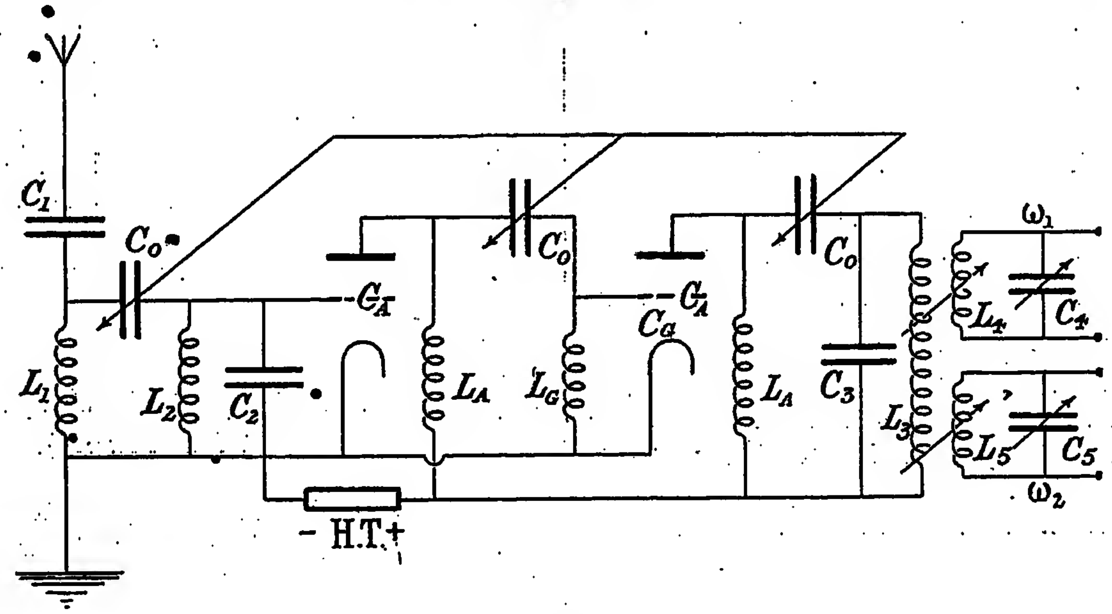

FIG. 6.

of C_0 therefore matters little as long as it is not too small, thereby making its reactance comparable with that from anode or grid to earth. Thus, with C_0 variable the amplifier will still amplify signals at the fixed frequency $\omega_1/2\pi$ as long as C_0 is not too small.

If, therefore, such an amplifier were connected as shown in Fig. 6, where $L_1C_1 = L_2C_2 = L_AC_A = L_GC_G = L_3C_3 = L_4C_4$, it will be possible to receive on this particular fixed wave-length simultaneously with reception on a variable wave-length depending on the values of C_0. L_5C_5 will be tuned to this latter variable frequency, so that the two frequencies are separated in the two detector circuits. This arrangement only allows the amplifier to receive signals at wave-lengths equal to or greater than that of the fixed wave-length determined by the product L_1C_1. By using an inductance coupling the variable wave-length can be made less than $2\pi v\sqrt{(L_1C_1)}$ and the complete range of wave-lengths could, therefore, be obtained by using a condenser and inductance in parallel. In this form it is not a practical proposition, because the inductance will not prevent the high-tension battery from affecting the grid of the valve. The difficulty can, however, be overcome by putting the parallel coupling unit in series with a fixed condenser of very large value, and therefore of very low impedance compared with that of the controlling unit. This design of amplifier is easily tuneable to any frequency in addition to the fixed frequency, but, as with all other amplifiers, is subject to self-oscillation after four or five such systems have been placed in cascade unless special means of preventing such oscillations are employed. Such a system is, however, economical in both amplifiers and aerials and is very easy to operate.

INSTITUTION NOTES.

Associate Membership Examination Results.

APRIL 1924, SUPPLEMENTARY LIST.*

Passed.

Batham, G. S. M. (New Zealand).

Passed Part II only.

Dalton, G. A. (South Africa).

AUGUST 1924, OFFICERS OF THE ROYAL CORPS OF SIGNALS.

Passed.

Allen, Capt. F. J. (P.W.O. Scinde Horse).
Bowen, Capt. W. O. (1/6th Gurkha Rifles).
Brown, Lieut. J. H. [Royal Garrison Artillery ("B" Corps Signals, India)].
Cameron-Webb, Capt. J. H. (1/11th Sikh Regt.).
Galwey, Lieut. W. C. V. (King's Own Royal Regt.).
Gemmell, Capt. G. W. (2/7th Rajputana Regt.).
Hardisty, 2/Lt. R. W. [47/2nd London Divisional Signals (T.A.)].
Kennard, Lieut. W. G. L. (Royal Field Artillery).
Knowles, Lieut. C. (Rifle Brigade).
Penney, Lieut. C. H. L. (Royal Field Artillery).
Rosenberg, Lieut. R. L. M. [Royal Garrison Artillery ("B" Divisional Signals, India)].
Schneider, Lieut. L. W. (Royal Field Artillery).
Tayleur, Capt. G. (4/2nd Punjab Regt.).
Walford, Lieut. J. E. S. (Worcestershire Regt.).
Wheatley, Lieut. M. S. (Dorset Regt.).
Williams, Lt.-Col. T. R. (Australian Staff Corps).
Willoughby, Capt. B. D. (P.W.O. Scinde Horse).
Wiseman, Lieut. H. J. (Durham Light Infantry).

* See p. 558.

National Certificates and Diplomas in Electrical Engineering.

The following is a further list of colleges and schools which have been approved under the scheme drawn up by the Board of Education and the Institution (see *Institution Notes*, No. 39, page 18, July 1923, and *Journal I.E.E.*, 1924, vol. 62, pages 209 and 381).

Approved for Ordinary Grade Certificates (Senior Part-Time Courses).

Wigan and District Mining and Technical College.
Watford School of Science and Commerce.

The Benevolent Fund.

The following is a list of the Donations received during the period 26 August–25 September, 1924 :—

	£	s.	d.
Dalton, W. T. (Newcastle-on-Tyne)	1	1	0
Davies, William (Chirk)		5	0
Dickin, H. C. (Derby)		6	0
Felix-Smith, L. E. (Auckland, N.Z.)		5	0
Jakeman, R. G. (Birmingham)		5	0
King, C. D. (Worcester)		5	0
Midland Electrical Engineers' Ball Committee	21	0	0
Walter, C. M. (Birmingham)	1	1	0

THE ECONOMICS OF POWER CONSUMPTION.*

(WITH SPECIAL REFERENCE TO SMALL D.C. MOTORS.)

By D. J. Bolton, B.Sc. (Eng.), Associate Member.

(*Paper first received 6th March, and in final form 16th June, 1924.*)

Summary.

The possibility of determining the frame size of a motor on economic instead of physical grounds is first discussed, and a basis is laid down for economic comparisons. The capital and working charges are considered in turn, and in connection with the latter the efficiency of a shunt motor when suitably under-run is examined. Applying this method to the case where $\frac{1}{8}$ h.p. at 1 000 r.p.m. is required, the economical position is indicated for various conditions of service and prices of energy, and it is found that a $\frac{1}{6}$-h.p. or $\frac{1}{4}$-h.p. frame is preferable in all but exceptional cases. Applying the method to sizes ranging from $\frac{1}{4}$ h.p. to 15 h.p. similar results are obtained, and it is found that the usual physical criteria are only satisfactory as a sole basis of choice when energy is exceptionally cheap or hours of service are short. The possible extension of the method and the effect of various changes are briefly reviewed.

It is characteristic of many physical operations—notably that of the flow of current in a conductor or of magnetic flux in an iron circuit—that the losses are dependent upon the density. It follows that in any relatively simple piece of apparatus, such as a bare conductor (and, to a lesser degree, a cable, a transformer or even an electric motor), the larger the apparatus selected for a given purpose the smaller will be the loss. Hence in totalling the cost of performing any given service the cost of the plant and the cost of the energy wasted are reciprocally related with reference to the plant size, and one particular size will frequently indicate a minimum total cost.

It will be seen from the above that there are two entirely different and unrelated methods of fixing the size of plant to perform a given service. On the one hand there are the usual physical limits of heating, sparking, overloads, etc., and when the size selected is the minimum necessary to comply with some such specification it will be here referred to as the *physical* choice. On the other hand the size may be fixed so as to give the least total expenditure on plant plus upkeep, and this will be referred to as the *economic* choice. The determination of this position—known by economists as the point of maximum return, and found by Lord Kelvin in the case of a plain conductor—will here be attempted in the more complex case of a direct-current motor, and its size will be compared with the corresponding physical choice.

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In view of the increased interest in economics of recent years, both in this country and in America, and of its many applications (such as scientific costing) in engineering production, it is surprising that there has been so little attempt at the costing of the *consumption* of engineering products. This may be due to the general backwardness of the consumer (in science and enterprise) as compared with the producer, even when the two are the same person in different capacities; and also to the fact that the manufacturer, however anxious to save himself expense, is not always so careful to do as much for his client. Much more is it due to the belief that in almost every case the economic choice will indicate a size smaller than that permissible on physical grounds, and will therefore be inadmissible on this account. This assumption is examined in the case of small d.c. motors in the present paper.

It will be clear from the above that the ordinary processes of design and selection do not neglect economics, but in paying exclusive attention to the physical limits of the materials employed they are all based on the assumption that the less the materials used the lower will be the cost. It follows that when a new point of view is brought in—that of the consumer—and the manufacturer's economy or "cost of article" is broadened to become "cost of service," a new basis will be established both for the design and for the selection. Primarily it is a problem for the designer, since if more money than necessary is to be spent on the plant in order that less need be spent on its upkeep, the most useful field for such expenditure will usually lie in the direction of improved quality of iron and insulation and better space utilization, rather than in a mere all-round increase in the quantity of the materials employed.

In spite of these facts this paper has been written from an entirely different point of view—that of the individual power user—and one way of putting its conclusions into practice consists simply in choosing a standard machine from the maker's list, of a larger size than the physical minimum. The reasons for thus leaving the more promising field of design and treating only that of selection are, in the first place, that the designer has no particular interest in reducing the cost of a service, and, if he had, would never persuade the majority of purchasers to pay more for their motors—action in this case must be primarily individual. In the second place, the manufacturing costs of qualitative departures from standard are extremely difficult to compute beforehand, whereas the data used in this

paper are the result of past experience and are generally available without the need for "inside information." Thirdly, it will be clear that if a case can be made out for using larger (standard) frames there will be a far better case for the design of special machines of higher quality wherever this is commercially practicable.

With particular regard to the last-mentioned possibility, the cases selected for treatment here are the smaller sizes—from fractional horse-powers up to 15 h.p., commencing with direct-current machines. In such cases the individual user may be a large-scale purchaser, employing the machines for ventilation, loom driving, etc., and may be in a position to commission qualitative alterations if the calculations indicate that this is likely to be advantageous. Another advantage which may appear in small sizes is that, the efficiencies being so low, the margin for improvement is considerable and its cost slight, but it must not be forgotten that the value of a given efficiency improvement is larger the greater the output.

It will be clear that there are a great many different economic problems in connection with the choice of a power unit. For instance, there might be alternative sorts of supply, or the type or speed of the unit might be in question. In most cases, however, the physical limits and local conditions will determine these matters, and the only problems here dealt with concern the choice of a motor to give a fixed power and speed for a given number of hours a year. The simplest of such problems arises when there are only two alternatives, as when the same or rival makers quote different efficiencies at correspondingly different prices, but it is rare thus to get a pair of machines which are identical in all other respects. In the cases dealt with below, a range of alternatives will therefore be considered and the exact point of economic choice will be indicated.

The first steps in solving any economic problem are to decide the basis of the comparison and then to tabulate on this basis all the expenses involved. The most usual basis, and much the best in this case, is that of annual costs, assuming the service to continue indefinitely. Thus if the service required is 5 h.p. at 1 000 r.p.m., it will be assumed that a suitable motor is purchased, and at the end of its life is replaced by another, and so on, all expenses being reckoned on an annual basis. As it is convenient to have a separate name for these regularly recurring expenses, all costs reckoned on an annual basis are here called "charges."

Reference has already been made to the fact that almost all kinds of operation involve two elements—the machine or structure made use of, and the labour, energy, etc., necessary for its performance. In making a schedule of the annual cost of performing the operation there are therefore two main groups, the "capital" or overhead charges necessary to provide and renew the plant, and the "work" charges necessary to operate it. Referring to these as the C and W components respectively, it will be seen that the former are chiefly financial and are largely independent of whether or not the machine is in use, whilst the latter are chiefly materials, labour, coal and electrical energy.

The actual preparation of a complete schedule of the charges involved in any service would be an extremely long affair, but it can be greatly simplified by omitting every item not affected by the change in question. Bearing in mind that the only alteration proposed is the substitution of a machine having a larger frame than the minimum size physically necessary, the following assumptions will be made:—

(1) That the only change in the capital charges will be the increase due to the substitution of interest and depreciation on the larger capital outlay (adjusted possibly for a longer estimated life). This assumes that there is no additional charge due to such items as insurance or additional floor space, etc.

(2) That the only change in the work charges will be the decrease due to the improved efficiency. This assumes that other items involved in the upkeep, such as repairs, etc., are unaltered. In order to simplify this item still further, the actual input watts to the motor will be divided into two portions, the one (equal to the output) which can be regarded as transformed directly into useful power, and the other which supplies the losses. This "loss coefficient," as it has been called, is equal to $[(1/\text{efficiency}) - 1] \times$ output and is the only item considered in the following treatment.

It is now possible to visualize the form which the economic comparison is to take. Graphically it will consist in plotting, to a base representing frame sizes to some suitable scale and commencing with the minimum size physically necessary, two curves, C and W, representing the structural and operation charges respectively, or rather such portions of them as are affected by the change in frame size. The former curve will rise and the latter will fall with the increase in frame size, and their sum will indicate total charges and should show a position of minimum charge which may or may not lie to the right of the physical frame minimum. The same thing can be done algebraically by expressing all charges as constants or variables relative to the frame size. A point of the latter is then found at which the rate of change of the two groups of charges is equal and opposite, and if this point indicates a larger frame than the physical minimum it will be economically sound to choose this one.

It will be noticed that this operation is strictly comparable with the application of Kelvin's law to cables. In the case of cables the independent variable is the area of the conductor, and (being a simple homogeneous material) both the watts lost and, usually, the cost of the whole cable are linear functions of it, and an algebraic solution becomes easily possible. In the case of motors, one is dealing with a complex structure in which both losses and costs are made up of a number of elements, and, although empirical formulæ can be developed, a graphical solution is usually preferable.

A difficulty arises as to the choice of scale for the base line of the curves. Whilst representing in all cases the size of the structure or frame there are various ways in which this can be measured, the most obvious being to plot with an even or logarithmic scale the maximum horse-power outputs which the frames are

rated to give. Instead of doing this, however, the author has found it best to choose a scale such that either the W or the C curve is a straight line, and these two methods are illustrated in the two cases treated in this paper, an even scale being employed in each case. In the former case the scale indicates watts saved per h.p. output, i.e. the values [(1/efficiency) − 1] are plotted from the right-hand side. In the second method the base divisions represent motor first cost, or, more strictly, annual expenditure on account of first cost, so that the C line is straight.

In a service which continues indefinitely there will come a continually recurring time at which the structure is worn out and has to be replaced. This necessity may arise through an actual failure to function, through a rapidly increasing repair bill, or merely because fresh inventions have improved the alternative structures available. In any case the owner must be presumed to make the change whenever it pays to do so, the length of the period being termed the "economic life," and the value of the old structure at the end of it (after deducting the cost of removal) the "salvage value." Looked at from an annual point of view, this necessity for periodic replacement is termed "depreciation" or annual loss of value on the part of the structure, although the actual "use value" to the owner may not diminish until the machine is finally discarded.

For the solution of the problems considered below it is necessary to find the annual figure which represents the cost of this periodic replacement, this being the amount which any sound concern should lay aside each year to amortise the liability. The particular financial arrangements by which this deposit is made, or the particular accounting arrangements by which it is equated to the annual depreciation in the yearly balance sheets, do not matter here, as, provided they are efficiently conducted, all the alternative methods will have (economically) the same result. It will therefore be convenient to assume the "sinking fund" method in which the equal annual deposits earn compound interest at the rate paid on the original loan, and are so chosen as to amount to the required figure at the end of the economic life.

Let C = first cost,
S = salvage value,
L = length of economic life, in years,
i = rate of interest on capital,
d_L = rate of sinking fund deposit, i.e. the annual end-of-year deposit which will realize unity at the end of L years.

Then $$d_L = \frac{i}{(1+i)^L - 1}.*$$

Just as with interest rates, this deposit figure can conveniently be given as a percentage, and is more usually taken from a table than worked out by formula. Table 1 is a convenient abbreviated table for percentage deposits ($100\,d_L$).

Using the above symbols it will be seen that the total capital charges consist of Ci units per annum for hire, and $(C - S)d_L$ for replacement of the plant employed. Where the salvage value is small or where it is a constant proportion of the first cost, the second item can be put Cd_L', where d_L' is the equivalent annual deposit $[d_L \times (C - S)/C]$. The capital charge then becomes $C(i + d_L')$, or, as it is usually termed, "interest and depreciation on the capital cost." Thus if interest is at 5 per cent, the life 16 years and the salvage value S is one-tenth of the first cost C, the total rate for hire and replacement will be $0{\cdot}05 + 0{\cdot}0423 \times 9/10 = 0{\cdot}088$, and the total capital charge will be $0{\cdot}088\,C$.

It has already been stated that the only item which is to be plotted for the W curve in the case of motors is that which represents the annual cost of supplying the machine losses, and which is referred to below as the "inefficiency" charge. The values of this curve will therefore depend upon two items which must first be considered—the conditions of service and the efficiencies of the motors when running below their rated output.

TABLE 1.

Life L	End-of-year deposit to realize £100 in L years with compound interest at—		
	4 per cent	5 per cent	6 per cent
Years	£	£	£
10	8·33	7·95	7·59
11	7·41	7·04	6·68
12	6·66	6·28	5·93
13	6·01	5·65	5·30
14	5·47	5·10	4·76
15	4·99	4·63	4·30
16	4·58	4·23	3·90
17	4·22	3·87	3·54
18	3·90	3·55	3·24
19	3·61	3·27	2·96
20	3·36	3·02	2·72

It will be clear that the expense of providing a given power in watts for, say, 1 000 hours a year with energy at 1d. per unit will be the same as for 2 000 hours at ½d. per unit, and it is therefore useful to have a composite term indicating the product of these two factors. The author has used the term "service-price" to indicate the hours of service per year multiplied by the price of energy in £, or the cost in £ of taking 1 kW for the number of hours per year for which the plant in question is connected. Thus for a plant connected for 8 hours per day and 300 days per year to mains with energy at 1d. per unit (or 24 hours a day with energy at ⅓d. per unit) the "service-price" would be 10. Thus the working charge W, i.e. the annual cost of wasted energy in £ = service price ÷ 1 000 per watt of inefficiency.

With regard to the efficiencies of motors which are permanently and intentionally under-run it might be thought that the ordinary efficiency curve plotted to a base of output would correctly represent the performance, but this is not the case. When a motor designed for maximum efficiency at full load or thereabouts is run at a lower load than this, the efficiency falls not

* It will be noted that d_L is less than $1/L$ owing to the fact that the deposits earn interest—thus it becomes approximately half this amount in a 30-year life with interest at 5 per cent.

because it is necessarily less for the smaller input, but because the balance between the iron and copper losses has been upset. To find its true efficiency at a lower load it is necessary to re-design it, or else to under-run it with regard to pressure simultaneously with the current reduction.* Under these circumstances a given frame will give only slightly lower efficiency at a half or a quarter of its rated load than it does at full load.

In order to make this point clearer, suppose that a 1-h.p. shunt motor is to be run at about one-quarter of its load, and assume in the first place that the permeability of its field system is constant. If a 200-volt motor is selected and run at 100 volts, and loaded so as to take half full-load current, this means that the applied and back E.M.F.'s are both half their previous values, and, as the field is half what it was, this halved back E.M.F. will be produced by the same armature speed. In other words the speed will be the same as before. With the current and field each halved, the torque will be reduced to a quarter of its original value and (at the same speed) the power output will also be reduced in the same proportion. The armature and field copper losses will be one-quarter of their previous values, as will also the losses proportional to B^2. Hence current. The freedom from distortion of the field flux depends upon the *ratio* of the field and armature ampere-turns, and in fact, with each of these reduced to one-half, a slightly "stiffer" field can be anticipated, since with better permeability the tendency of the flux to spray will be diminished. Moreover, although the commutating E.M.F. for a given brush position will be halved, the armature current requiring reversal will also be halved. This point, like the other, was amply borne out by the tests referred to, and in no case was the commutation noticeably inferior to that on full load.

It must not be supposed that merely to select a large standard machine and under-run it on the above lines is in any way to be recommended as ideal, since in all cases some degree of re-design or rearrangement is preferable. All that is claimed is that such a course is quite practicable, even down to one-quarter of the rated output (at which point the running is liable to become unstable), whilst for small changes it may well prove to be the most economical way of increasing the iron and copper sections. In any case it provides a convenient hypothetical course of action, by means of which the economic advantages of plant-increases can be tested.

TABLE 2.

Column 1 Frame	Column 2 Rated load	Column 3 Full-load efficiency	Column 4 Price	Column 5 Estimated life, L	Column 6 Capital charge	Column 7 Estimated efficiency when giving $\frac{1}{8}$ h.p.	Column 8 Corresponding losses
	h.p.	per cent	£ s. d.	years	£	per cent	watts
a	$\frac{1}{8}$	53·5	5 16 0	10	0·750	53·5	81
b	$\frac{1}{6}$	63	6 12 0	11	0·800	59·6	63
c	$\frac{1}{4}$	67	7 15 6	12	0·877	62·4	56
d	$\frac{1}{2}$	72	11 15 0	14	1·187	60·2	61·5
e	1	74·5	18 18 0	16	1·740	—	—

it will be only the friction, windage and a small proportion of the iron losses which will prevent the efficiency remaining constant and will cause the curve to tilt downwards slightly on the lower inputs. Furthermore, as the permeability will actually not be constant but will be considerably better at the lower exciting voltage, the speed on half voltage will be less than normal and will have to be brought up either by means of the field resistance or by fitting a different set of field coils. Even in the former case the field loss will then be less than one-quarter of the full-load value, and this will still further tend to keep up the efficiency.

With a view to a practical confirmation of the above reasoning, the author had a number of tests made on small shunt machines of the sizes dealt with in this paper and in no case was there any marked reduction of efficiency down to one-quarter of the rated output.

It might be anticipated that the commutation of such under-run machines would be impossible on account of the weakening of the field, but this will be found to be fully balanced by the reduction in the armature

* The advantage of doing this will, of course, depend upon the proportions of the different losses. If the armature I^2R loss is greater than the sum of the iron and field losses, the ordinary method of under-running will be preferable: but if (as is more likely) these latter are the greater, it will be preferable to under-run the pressure even more than the current if the commutation permits.

FRACTIONAL HORSE-POWER SERVICE.

The first case to be considered is where the service required is $\frac{1}{8}$ h.p. at 1 000 r.p.m. from a shunt motor on d.c. mains. A number of quotations were obtained for motors of this speed ranging from $\frac{1}{8}$ h.p. to 1 h.p., and one set of these, as shown in the first four columns of Table 2, was selected. (All of these figures were taken from a single quotation, dated December 1923, with the exception of frame *b* which was taken from a precisely similar range of machines by another maker. In all cases except the first the prices include an extra for supplying to a non-standard voltage. The selection of a quotation was made as far as possible with a view to getting a typical as well as a sufficiently continuous range of figures, but from a comparison with figures given later it would appear that the efficiencies of the $\frac{1}{4}$-h.p. to 1-h.p. sizes is slightly above the average usually obtained.)

The position then is that a certain service is required, for which machine *a* costing £5 16s. and having an efficiency of 53·5 per cent is physically adequate. But by spending more money on the machine (a tendency represented by frames *b* to *e*) higher efficiencies can be obtained, and the problem is to find out to what extent

(if any) this tendency should be followed. The first step is to estimate the probable lives and efficiencies of the larger machines when performing the $\frac{1}{8}$-h.p. service.

With regard to lives, that of machine *a* has been taken as 10 years, but it is reasonable to suppose that the lives of the larger machines will be progressively greater, both intrinsically and because they are giving so much less than their rated output. These lives are therefore taken as ranging from 11 to 16 years, as shown in col. 5, and taking interest at 5 per cent and salvage value zero, the figures in col. 6 are obtained by multiplying the first cost by the sum of the rates for hire plus replacement, as mentioned earlier in the paper.

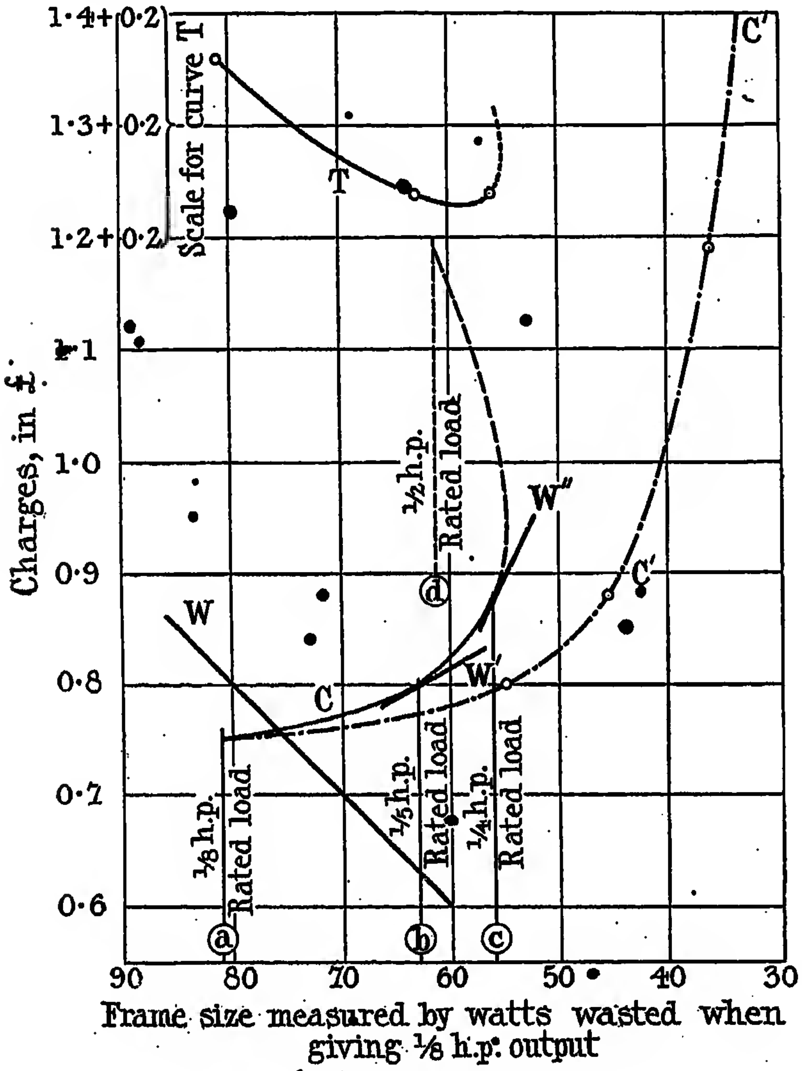

Fig. 1.—Fractional horse-powers.

With regard to the efficiencies of the larger machines when under-run, and assuming suitable selection as regards voltage, etc., reasons have already been given for supposing that in the majority of cases, particularly if the normal flux density is high or if the range of selection is not limited entirely by the printed price-list, the full-load efficiency can be maintained almost intact down to one-half or less of the output. On the other hand, in a small machine, particularly if run at a high speed, the friction and other "constant" losses (not reducible by pressure or current reductions) may constitute a considerable proportion of the whole, and in order to make a conservative estimate, and also to illustrate the method as fully as possible, it will be assumed that in this case the irreducible losses amount to one-sixth of the total full-load loss. Col. 7 shows the estimated efficiency (when giving $\frac{1}{8}$ h.p.) calculated on this basis, and it will be noticed that this rules out frames *d* and *e*.

The losses at $\frac{1}{8}$ h.p. output, corresponding to these efficiencies, are shown in col. 8, and these figures are used as the abscissæ in Fig. 1. The base of this graph represents, in general terms, the frame size, but the actual scale employed is that of watts saved, so that the values [(1/efficiency) — 1] × 746/8 are scaled off from the right-hand side. On the above basis the upright lines, a, b, c and d, represent the first four frames quoted, and marking off ordinates to represent the corresponding capital charges the curve C is obtained. (Had the full-load efficiencies been maintainable for all degrees of under-running, the upright lines representing frames *b* to *d* would occur more to the right, and the chain-dotted curve C′ would have been obtained, frame *d* being now a useful contribution.) Curve C therefore represents the annual cost of saving energy by means of larger plant equipment; it rises slowly at first, but more steeply later, when the gain in efficiency for additional expenditure becomes steadily less.

With the base scale chosen it will be clear that curve W representing the annual cost of the energy wasted in the motor will be a straight line depending upon the annual hours of service and the price of energy. It has been seen that for a "service-price" of 10 (e.g. 8 hours × 300 days with energy at 1d. per unit) the working charge is £0·01 per watt of inefficiency, and this gives a line W at 45° to the axes. Adding curves C and W gives a total curve T * which shows a minimum somewhere between frames *b* and *c*.

For any other service-price the line W will have a difference inclination, and, in order to avoid redrawing, it can be reversed and made tangential to curve C at some point which will then indicate the economic position. Thus energy at half the above price, or hours of service proportionally shorter, would be represented by the reversed curve W′ which is tangential to curve C exactly at frame size *b*. On the other hand, a bigger service price, e.g. 20, would be represented by curve W″ which is tangential at about frame size *c*.

The economic advantages of under-running are here very apparent. Assuming a normal working day it will be seen that even with energy at only $\frac{1}{2}$d. per unit it will pay to employ the next larger size of machine, whilst with dearer energy a still larger frame (or better still the same frame re-designed) is called for. The slope of curve C at its commencement is less than half that of W′, showing that frame *a* is only economical for its rated output when energy costs less than $\frac{1}{4}$d. per unit.

Larger Horse-powers.

An attempt will now be made to extend the above method to the case of somewhat larger motors, and in so doing to construct a curve that can be used for a number of different horse-powers and conditions of service. For this purpose it has been thought best to take an average set of figures rather than one individual quotation, and in cols. 2 and 5 in Table 3 will be found the average of some half-a-dozen makers' net prices and full-load efficiencies for machines having rated outputs from $\frac{1}{2}$ h.p. to 15 h.p.

* For convenience this curve has been plotted minus £0·

The base of the curves to be drawn will represent (as before) the size of the structure, but the scale in this case is in units of annual capital costs (hire plus replacement) so that the "capital charges" curve C will be a straight line. The lives have been taken as ranging from 12 to 20 years (col. 3), with a salvage value of 10 per cent of the first cost in each case; and the figures in col. 4 are then obtained by using the interest table already given. These are used along the base scale (Fig. 2) to erect 13 upright lines representing the 13 frame sizes, having the maximum output ratings shown and costing each year in hire and replacement the amounts scaled along the base. As the ordinate scale in £ is the same as the base scale, a line C at 45° will represent the annual expense on account of structure (capital charge).

It will here be assumed that within the range of under-running proposed (usually not more than down to one-half the rated output) the full-load efficiency can be maintained intact by a suitable choice of voltage, etc.* Marking off these full-load efficiencies on the 13 upright lines and drawing a smooth curve through the points gives the curve shown at the bottom of Fig. 2, and it will be seen that (provided the makers' ratings fit in) it is possible, for an annual expenditure on hire and replacement of, say, £2, to purchase a frame having an efficiency of just over 78 per cent. The heating and sparking limit of this frame will prevent it being used above about 2½ h.p., but for the moment it will be convenient to neglect temperature limits entirely and proceed as though any frame could be used for any output whatever.

Above the efficiency curve and to the same base has been plotted its reciprocal the "loss coefficient" or "percentage loss" curve W, showing how the loss for any given output decreases with an increase in the size of frame employed. This curve will represent to some suitable vertical scale the annual cost of supplying the wasted energy, but the scale will depend not only upon the output but also upon the hours of service and price of energy. Thus each particular horse-power and set of service conditions will have a particular W curve of the shape shown.

Reference has already been made to the term "service-price" to indicate the annual hours of service multiplied by price of energy (£) and it here becomes necessary to group with this the power output, and to use the term "power-service-price" to indicate the product of the horse-power multiplied by the service-price. Since the power wasted in a motor equals [(1/efficiency) — 1] × output it follows that the annual cost of this in £ will be [(1/efficiency) — 1] × 746/1 000 × power-service-price. In Fig. 2 curve W is for a power-service-price of 10, e.g. for a 1-h.p. motor running 8 hours a day for 300 days with energy at 1d. per unit, or 24 × 300 hours with energy at ⅓d. per unit, and as the vertical scale is in £ the values for W are obtained from the expression [(1/efficiency) — 1] × 7·46 (col. 6).

It is now possible to add together curves C and W, giving a total T which shows a minimum just above the frame rated for a maximum of 1½ h.p. Thus for the output and service mentioned above, or for an even smaller power, if energy were more expensive it would be economically sound to purchase the 1½-h.p. frame and under-run it to this extent. In the case of energy costing ½d. or less per unit and where the motor runs 8 hours a day it will be seen that this frame size would be economical for outputs of 2 h.p. or over—in other

TABLE 3.

1 000-*r.p.m. Shunt Protected d.c. Motors.*

Column 1 Rated load	Column 2 First cost	Column 3 Life	Column 4 Corresponding capital charge	Column 5 Rated full-load efficiency	Column 6 (1/efficiency — 1) × 7·46 (Working charge, P.S.P.† = 10)	Column 7 Economical P.S.P.†	Column 8 Economical service-price (Col. 7 ÷ Col. 1)
h.p.	£ s.	years	£	per cent	£		
¼	7 15	12	0·825	61·0	4·77	—	—
½	10 7	13	1·042	66·7	3·73	3·6	7·2
¾	12 4	14	1·17	70·2	3·17	5·0	6·7
1·0	14 8	15	1·32	71·8	2·91	6·2	6·2
1·5	17 10	16	1·54	75·7	2·39	8·9	5·9
2	20 0		1·76	77·0	2·24	11·4	5·7
3	26 8	17	2·24	78·6	2·02	19·2	6·4
4	29 10		2·50	79·9	1·88	24	6·0
5	32 7	18	2·65	80·9	1·77	27	5·4
7·5	37 4		3·05	82·4	1·59	38	5·1
10	44 16	19	3·57	83·6	1·47	50	5·0
12·5	50 0		3·97	84·0	1·42	—	—
15	57 8	20	4·42	84·2	1·40	—	—

† Power-service-price.

* It is, of course, true that if frictional losses were a substantial item many of the actual sizes shown in the table would have an appreciably poorer efficiency if run at the next smaller listed rating. But the particular sizes listed must be regarded primarily as landmarks or points on a curve showing the trend of the manufacturing cost of improving the efficiency. In addition, since intermediate sizes are made, the individual user will frequently be able profitably to employ one of these (with a smaller degree of under-running), particularly if he can also command small changes in design such as new field coils, etc.

words the usual physical criteria would be justified as the basis of choice.

In the case of some other value of the power-service-price, say 20 (i.e. 2 h.p. for 8 × 300 hours at 1d. per unit, or its equivalent), the curve W should be re-plotted, in this case twice as high. To avoid doing this the ordinate scale can be halved, which will have the effect

The procedure outlined above can be carried out algebraically, either on the basis provided by the graph or by using the calculus. In the former case it is advisable to plot the rate of change of the loss coefficient with reference to annual capital costs and to draw a smooth curve through the results. The reciprocals of these values are shown in col. 7 of the table and represent the

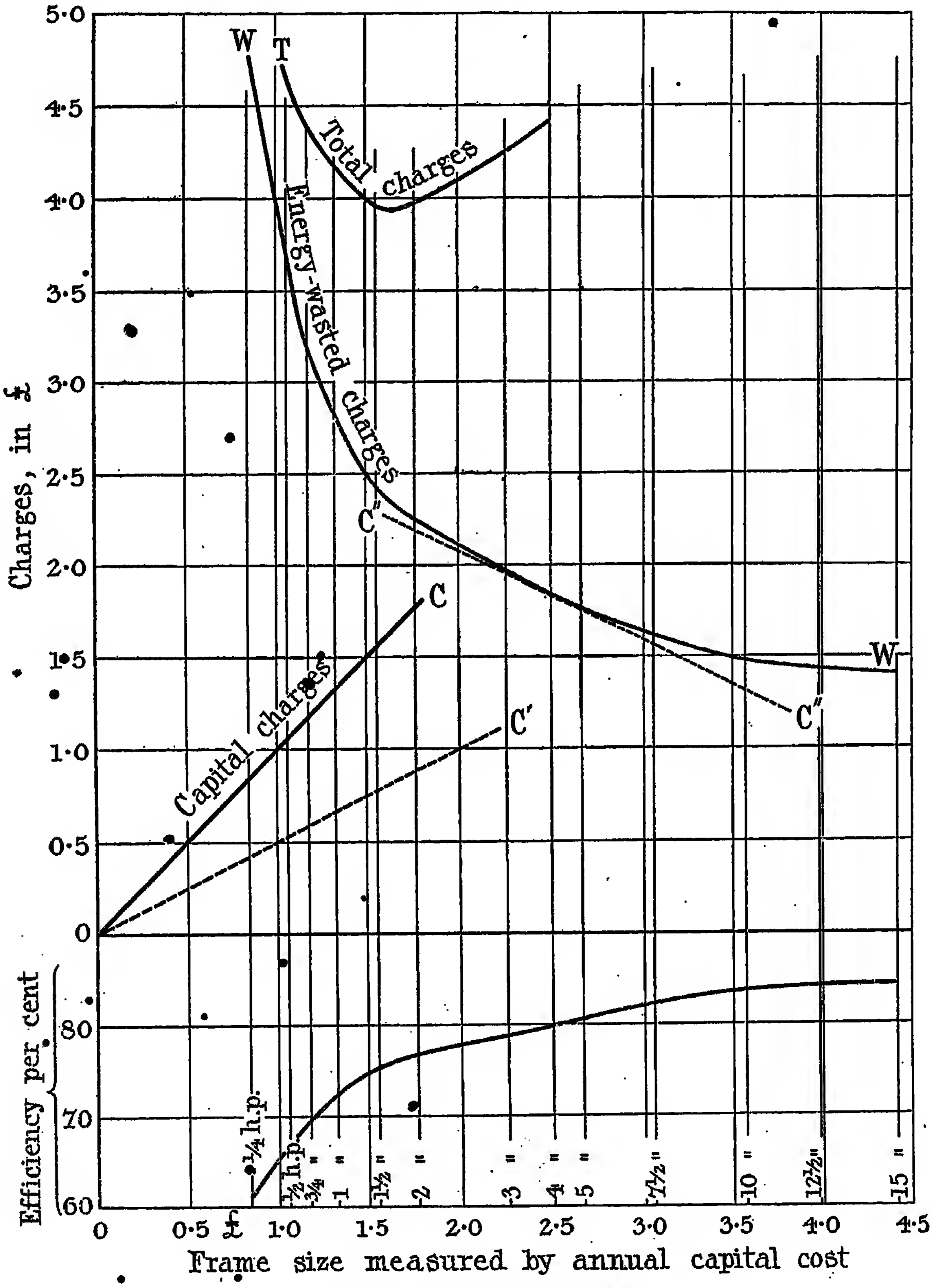

FIG. 2.—Larger horse-powers.

of bringing the capital charge curve to a new inclination (see dotted line C′). Instead of adding this to the W curve it can be reversed and then brought up to the latter in order to see at what point it is tangential (see dotted line C″). Thus it will be noticed that at or near the 4-h.p. frame the slopes of the two are the same, thus showing the economical position for this particular power-service-price.

power-service-price at which it would be economical to run the frame in question. Thus for a service-price of 10 it will be seen that the economical horse-powers are generally about half the physical output ratings.

In applying the calculus, the base scale previously used as the independent variable has been abandoned, and instead both charges have been calculated to a base of rated horse-power outputs (H). This serves as a

check on the graphical solution and in its turn can to some extent be checked by existing data which have been worked out on this basis. By plotting logarithms of the price and loss coefficient figures, empirical formulæ to some power of H can be devised for them both, although the latter requires several different formulæ to represent it accurately over the whole range.

From $\frac{1}{4}$ h.p. to 2 h.p. the loss coefficient (1/efficiency $- 1) = 0 \cdot 386\, H^{-0 \cdot 36}$ and hence the inefficiency charge $W = 0 \cdot 746 \times 0 \cdot 386\, H^{-0 \cdot 36} \times$ (power-service-price) in £. The price is found to be given by $14 \cdot 1\, H^{0 \cdot 5}$,* and taking a uniform life of 14 years for this range of sizes, and with interest at 5 per cent and salvage value 10 per cent of first cost, the capital charges $C = (0 \cdot 05 + 0 \cdot 051 \times 0 \cdot 9)\, 14 \cdot 1\, H^{0 \cdot 5}$. Adding these to get the total charge T, and differentiating with respect to H, T is found to be a minimum when

$$H = 0 \cdot 113 \text{ (power-service-price)}^{1 \cdot 16}$$

or when $\quad$ Power-service-price $= 6 \cdot 5\, H^{0 \cdot 86}$

Similarly from 3 to 10 h.p. the loss coefficient is $0 \cdot 36\, H^{-0 \cdot 26}$ and, taking a uniform life of 18 years and salvage value 10 per cent, T is found to be a minimum when $\quad H = 0 \cdot 061$ (power-service-price)$^{1 \cdot 32}$

or $\quad$ Power-service-price $= 8 \cdot 3\, H^{0 \cdot 76}$

The final expressions in both the above cases give values very similar to those in col. 7 in the table, allowing for graphical discrepancies and for differences in the estimated lives.

It will be understood that throughout this paper the object has been to demonstrate a method rather than to establish a result. Nevertheless, there are one or two conclusions which can be drawn, with some degree of certainty, in the case and with the figures treated above. If each quantity in col. 7 of the table is divided by that in the first column, a fairly uniform figure of 6 is obtained (col. 8), this being the service-price at which each particular frame size can be economically employed to give its actual rated output. For this particular length of service and price of energy the economic and the physical criteria coincide, and at 8 hours per day and 300 days per year this means energy at $0 \cdot 6$d. per kWh.

The above leads to the somewhat startling conclusion that for motors in use during an average working day the physical criteria by which alone they are at present selected become unsatisfactory when energy costs more than $0 \cdot 6$d. per unit. All cases at about these figures require to be considered on economical as well as physical grounds, and where energy costs 1d. or more per unit, a considerably larger machine will usually prove the cheaper installation.

More generally the results obtained may be said to prove two things: first that the extra expense of larger machines, as compared with the value of the energy they save, is far less than is generally realized; and secondly, that the advantage of under-running is no less marked on the larger than on the smaller powers and would emphatically appear to call for a general review of this question and a detailed consideration of all sizes of electric motors, both d.c. and a.c. It is not too much to suggest that such a review may lead to a complete revision of our methods of choosing motors for long-period service, future ratings being determined by economic considerations, whilst the heating properties, like the insulating properties, fix only a lower limit.

It only remains to consider one or two objections or modifications to the above, the chief of which concerns the question of what exactly constitutes the power of any particular service. In using the phrase "a 1-h.p. 1 000-r.p.m. service" it is assumed that 1 h.p. is the actual load whenever the motor is in use, or failing this the average load. Even if it is the former, many engineers would put in a $1\frac{1}{4}$-h.p. or $1\frac{1}{2}$-h.p. frame, and still more so if the 1 h.p. is an *average* output. Thus to speak of the 1 h.p. frame as the normal physical choice may be unfair to present-day choosers, many of whom may be yielding to an unconscious economic sense in specifying a larger machine than is necessary (although if so the application should be more scientific and should endeavour to under-run both the iron and the copper). More usually any under-running or over-specifying that may take place is with a view to possible overloads rather than on economic grounds, and it must be realized that the former is just as much a physical criterion as is the temperature-rise. Under-running on economic grounds is entirely distinct and takes different forms; thus a 2-h.p. frame under-run to give 1 h.p. on the lines suggested would *not* (unless re-designed) be suitable for giving 2 h.p. even occasionally, since its commutation would not be satisfactory. In the case of widely fluctuating loads it will be understood that although an approximate estimate might be made on the basis of the average load, this could not be considered very satisfactory, since the average efficiency of a machine whose copper loading alone was varied would be considerably below the maximum efficiency.

With regard to the factors likely to affect the results obtained above, the market prices of motors and energy are both fairly definite and fairly steady, but the rate of interest on capital is more problematical and would have to be adjusted to suit the circumstances of each individual case. Motors having a market value independent of the prosperity of the concerns in which they are used, should rank amongst the tangible assets paid for by debenture shares, and in this case the rate of interest on extra capital so employed need not be high; on the other hand, if their purchase is considered to involve a risk and has to be financed by more speculative investments, the rate of interest will naturally be higher. Two points should be noticed in this connection: first, the capital charge is not *proportional* to the rate of interest, since the depreciation item is less when the rate is greater; and secondly, a general alteration in the market rate of interest is unlikely to make any ultimate difference to the above results, since the price of energy is also to a large extent a function of interest on capital.

* L. A. Doggett in the *Electrical World* (1915, vol. 66, p. 746) gives the price of a new d.c. motor or generator as $4\,500 \left(\frac{\text{kW}}{\text{r.p.m.}}\right)^{0 \cdot 6}$ dollars, and although the difference in date makes it difficult to compare the two formulæ the similarity of the index figure is significant.

THE CURRENT-CARRYING CAPACITY OF SOLID BARE COPPER AND ALUMINIUM CONDUCTORS.*

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Summary.

The current-carrying capacity of bare copper and aluminum conductors is limited by the heating effects produced by the current. The dissipation of this heat is a function of the temperature elevation above the surrounding air, the size of the conductor, and the intrinsic condition of the surface. A cooling-curve method is described which was used in determining the coefficient of heat emissivity for a series of small sample lengths of round and flat copper and aluminium conductors of various sizes and surface conditions. This was checked by the direct electrical heating of longer lengths, which showed the two methods to be in close agreement. Tables for the current-carrying capacity of copper and aluminium busbars have been deduced from the constants obtained and are given in the paper.

An investigation was carried out on various sizes of round and flat copper and aluminium conductors ranging in diameter from $\frac{1}{2}$ in. to $1\frac{3}{4}$ in. in the case of round bars and from 1 in. × $\frac{1}{4}$ in. to 4 in. × $\frac{1}{2}$ in. in the case of the flat strips, in order to determine the rate of heat dissipation per unit area of exposed surface and the extent to which this is affected by the surface condition of the metal, and in the case of the flat strips by their position, i.e. whether vertical or horizontal. From the knowledge of this constant it then becomes possible to calculate the current-carrying capacity for any size of conductor for any given temperature-rise, if the resistivity of the metal at that temperature be known.

Two methods of determining the rate of heat dissipation are available; these may be called the "static" and the "dynamic" methods respectively. In the first the length of the bar, which must be sufficiently long to avoid any irregular heating or cooling effects at the ends (which will appreciably affect the result), is heated by the passage of a steady current and the temperature-rise is deduced from the change of resistance in the central portion, the temperature coefficient of a small sample cut from the bar having been previously determined. The change of resistance is most conveniently measured by means of a Kelvin double bridge and a standard resistance to which the conductor under investigation is connected in series.

The current must be maintained steady for a considerable period—in the larger bars some five or six hours—before the temperature-rise can be considered to have reached its maximum value. When this is attained the watts dissipated per unit length of the bar can be calculated from the current and the resistance (at that temperature). The temperature-rise is calculated from the change of resistance and from the specially determined value of the temperature coefficient. The heat dissipated per unit length of conductor is then equal to the square of the current multiplied by the resistance of unit length, or

$$W = I^2 r$$

where I is the current in amperes, and
r the resistance in ohms per unit length at the given temperature.

The average value of the heat dissipation per unit area is then W/p, where p is the perimeter of the section.

If θ is the temperature excess of the bar above the surrounding air, and assuming Newton's law of cooling, the heat dissipation per degree is

$$h = I^2 r / p\theta$$

But the heat dissipation is mainly due to convection and, since convection may be taken as being proportional to $\theta^{5/4}$, it is preferable to make use of this relation, in which case we have

$$h = I^2 r / p\theta^{5/4}$$

This method of deducing the value of h may be called the "static" method, since it is effected by measuring the amount of electrical energy dissipated as heat when the maximum temperature has been attained and conditions are stable. It involves, however, the use of a large amount of energy, especially when testing the larger-sized conductors, and the current must be maintained for a considerable time before stable conditions are reached. In order that the end-effects may not unduly affect the results it is necessary that the bars should be long, also that they should be shielded from extraneous draughts. This method was therefore used only as a control, and the majority of the results were obtained by an alternative method which may be called the "dynamic" method.

In the "dynamic" or cooling-curve method a short length (i.e. 1 or 2 ft.) of conductor bar can be used. It is heated in an oven until a suitable temperature elevation is obtained and is then placed in a draught-

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free enclosure and supported on two knife-edges of some material of low thermal conductivity. These knife-edges in the experimental determinations were V-sectioned pieces of mahogany, so that the heat escaping by conduction through the supports could be regarded as negligible. The temperature of the bar was measured by means of an iron-eureka thermo-couple embedded in a small hole drilled in the bar. A micro-ammeter in series with the thermo-couple was calibrated by means of a resistance in series to read directly the temperature difference between the bar and the surrounding air. The amount of this temperature difference at various intervals of time was measured and from the readings obtained the cooling curve was drawn. The deduction of the constant h from these observations is as follows: When the bar is cooling, and on the assumption that the rate of heat dissipation is proportional to the 5/4 power of the temperature excess,

$$-dH = -m\sigma d\theta = ph\theta^{5/4}dt \quad . \quad . \quad . \quad (1)$$

Where H is the quantity of heat per unit length of bar; m the mass per unit length; σ the specific heat (expressed in joules) of the metal under consideration; θ the temperature excess; p the perimeter of the section of the bar; t the time in seconds, and h the emissivity constant. Hence

$$d\theta/\theta^{5/4} = \frac{-ph\,dt}{m\sigma} \quad . \quad . \quad . \quad . \quad (2)$$

which leads to

$$1/\theta^{\frac{1}{4}} = \frac{ph}{4m\sigma}(t + 1/\theta_0^{\frac{1}{4}}) \quad . \quad . \quad . \quad . \quad (3)$$

where θ_0 is the initial temperature difference between the bar and the surrounding air. If therefore $1/\theta^{\frac{1}{4}}$ be plotted against t, a straight line should be obtained the slope of which is $ph/(4m\sigma)$. If the slope of the line be equated to $ph/(4m\sigma)$ we have

$$h = \frac{4m\sigma\,(\text{slope})}{p} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

A large number of observations were made on short lengths of various sizes of aluminium and copper conductor of both circular and rectangular cross-section—the latter in two positions, i.e. with the longer dimension (1) vertical and (2) horizontal. The effect of surface condition was also investigated and comparative tests were made on bars (1) left in their original condition, (2) cleaned with sandpaper, and (3) coated with various paints. The test bars were heated in the oven to about 100° C., and the cooling curve was taken down to 40° C. or 50° C. In all cases, on plotting $1/\theta^{\frac{1}{4}}$ against time a very satisfactory linear relation was obtained, as will be seen from the figures. This proves that over this range the assumption that the total heat emissivity is proportional to the 5/4 power of the temperature excess is very well justified.

The effect of these various factors on the heat emissivity will now be considered.

Flat Bars: Effect of Position.

As might be expected, the heat emissivity or mean emission of heat per unit area of the outer surface of a flat bar is very considerably affected by its position and is much greater when the bar is placed with the longer dimension of the cross-section vertical. The extent of this difference is shown in Table 1, which gives the ratio of the emissivities in the vertical and horizontal positions for various ratios of breadth b and thickness t of the cross-section for four flat aluminium bars ranging in size from $1\frac{1}{4}$ in. × $\frac{1}{4}$ in. to 4 in. × $\frac{1}{2}$ in.

Table 1.

Dimension of section	b/t	Ratio of emissivity: upright to horizontal
$1\frac{1}{4}$ in. × $\frac{1}{4}$ in.	5·0	1·16
2 in. × $\frac{3}{8}$ in.	5·3	1·26
$3\frac{1}{2}$ in. × $\frac{15}{32}$ in.	7·5	1·11
4 in. × $\frac{1}{2}$ in.	9·0	1·18
		mean 1·18

Graphs of $1/\theta^{\frac{1}{4}}$ plotted against t for the 2 in. × $\frac{3}{8}$ in. aluminium bar are shown in Fig. 1, together with the calculation of h from the slope for both the vertical and the horizontal position.

It will be seen that although the ratio b/t increases in a regular progression, the ratio of the two values of

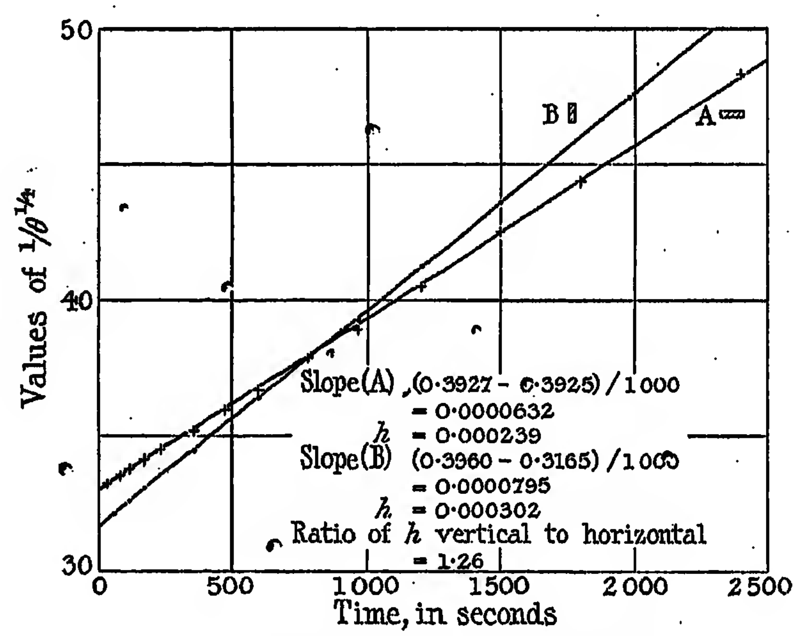

Fig. 1.—Effect of position on emissivity.

the emissivity varies somewhat erratically, being 1·26 for the 2 in. × $\frac{3}{8}$ in. strip and 1·11 for the $3\frac{1}{2}$ in. × $\frac{15}{32}$ in. strip. If 1·18 be taken as an average value of the ratio, then a flat conductor in the vertical position, all other things being equal, may be expected for the same temperature excess to dissipate approximately 18 per cent more heat than when in the horizontal position. This corresponds to an increase of about 9 per cent in the current-carrying capacity.

Effect of Surface Condition on Emissivity.

The effect of the condition of the surface is shown in Figs. (2), (3), (4) and (5), and in Table 2.

It will be noted that in the copper conductors the original condition was more favourable to the emission

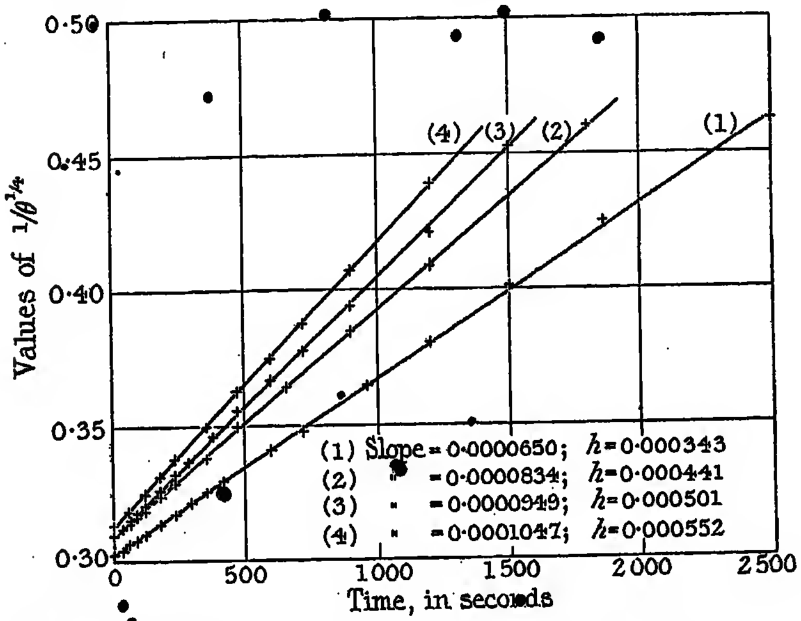

Fig. 2.—Effect of condition of surface: 2·22 cm round aluminium bar.

of heat than when the surface had been rubbed bright with sandpaper. The effect of painting the surface of the conductor a good dull black was to increase the emissivity by about 40 per cent and the current-carrying capacity for the same temperature-rise by

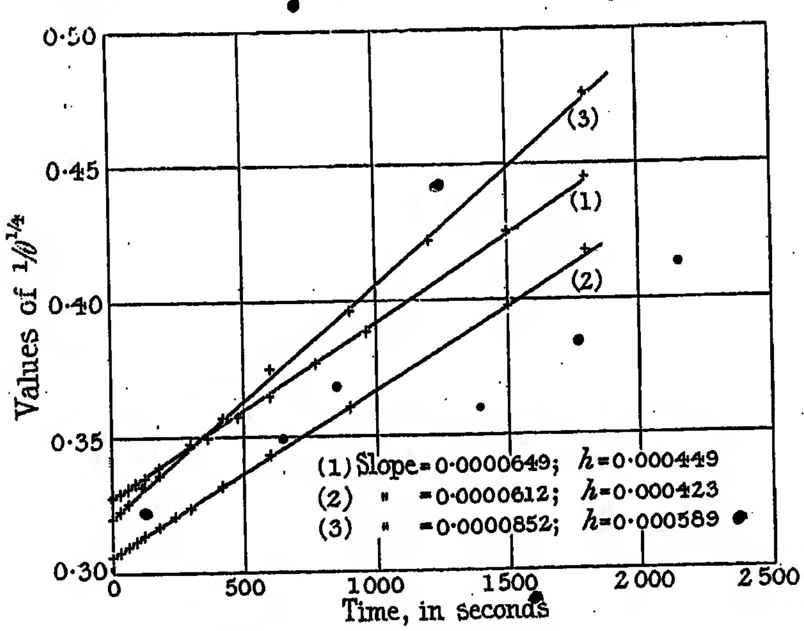

Fig. 3.—Effect of condition of surface: 1·9 cm round copper bar.

about 20 per cent. By the use of the best dull black paint available these values were increased to about 54 per cent and 24 per cent respectively.

Effect of Size of Conductor on Mean Emissivity.

As is well known, the heat emissivity, i.e. the amount of heat (conveniently expressed in watts) which is on the average emitted from each square centimetre of the surface of the conductor per degree of temperature difference, varies with the cross-section of the conductor. Both in round and in flat bars h is greater for small bars than for large ones. In order to investigate the nature and amount of this variation all the bars available of both round and rectangular cross-section were first painted with the same special dull

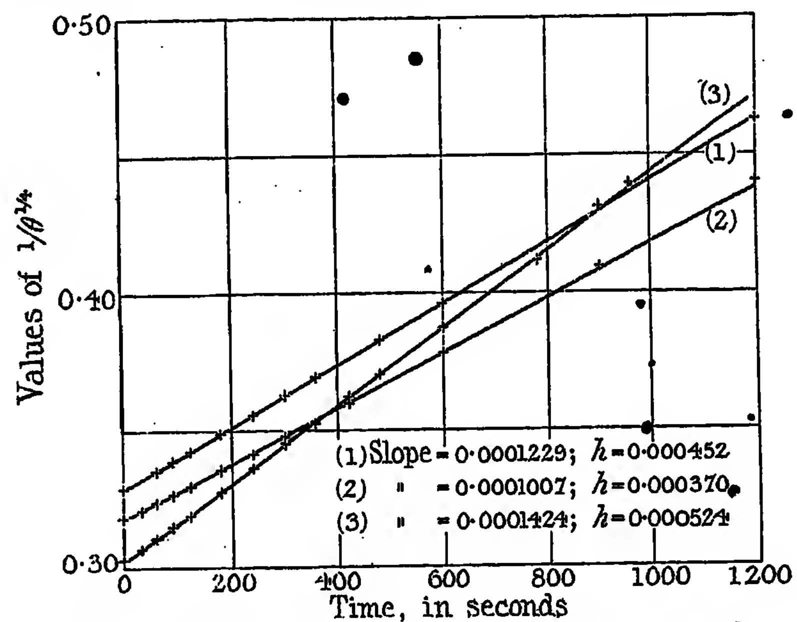

Fig. 4.—Effect of condition of surface: $1\frac{1}{2}$ in. × $\frac{1}{4}$ in. flat copper strip.

black paint so that the condition of the surfaces should be the same in all, and the value of h for each bar was then determined by the cooling-curve method. The rectangular bars—which were all aluminium—were taken with the longer dimension of the cross-section

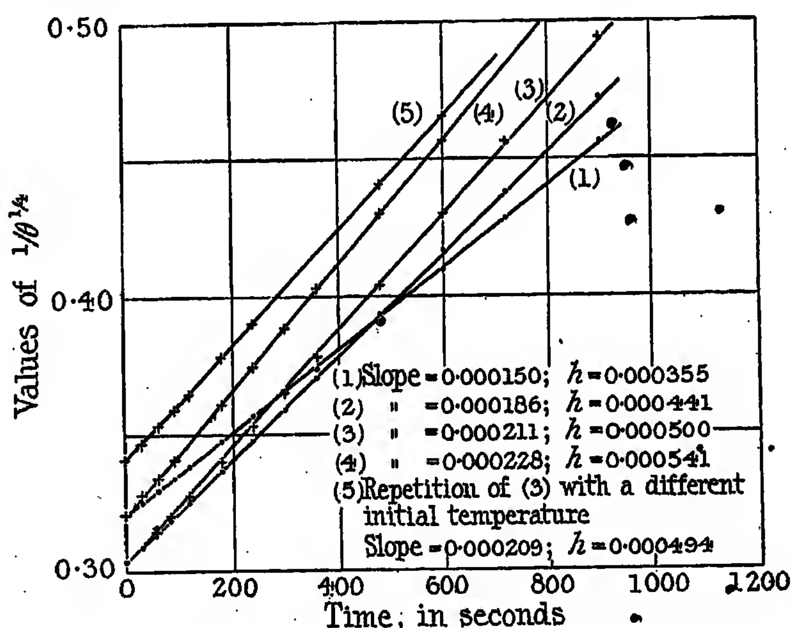

Fig. 5.—Effect of condition of surface: 1 in. × $\frac{1}{4}$ in. flat aluminium strip.

vertical. The round bars included both copper and aluminium. The results obtained are given in Table 3.

Corresponding values of p and h are also shown plotted in Fig. 6, the crosses referring to the flat and the small circles to the round bars. It will be seen that the points all lie along one well-defined and fairly regular curve, the divergence of any point from the mean curve not exceeding 2 per cent and being usually much closer. The values of h for flat bars in the horizontal position, assuming the relation of 1 : 1·18 as

explained in a preceding section, have also been computed and have been added for comparison.

In order to obtain an expression for the mathematical relation of h to p, the logarithms of these quantities, which are also given in Table 3, have been plotted and are found to lie in a fairly straight line. The divergence of the least favourable point from the best mean line is of the order of − 3 per cent. The ture difference between the bar and the surrounding air.

This relation refers to bars painted with a specially good dull black paint of high emissivity. The values obtained by this formula should therefore be reduced by about 8 per cent (see Table 2) where dull black paint of ordinary quality is used.[6]

The effect of variation of the perimeter of the bar

TABLE 2.

Size and type of conductor	Condition of surface	Watts per cm² per deg. C. (h)	Relative current-carrying capacity compared with original condition
2·22 cm round aluminium bar (see Fig. 2)	(1) original	0·000343	1·00
	(2) black (glossy)	0·000441	1·13
	(3) black (dull)	0·000501	1·21
	(4) special dull black	0·000552	1·27
1·9 cm round copper bar (see Fig. 3)	(1) slightly tarnished	0·000449	1·00
	(2) bright	0·000423	0·97
	(3) black (glossy)	0·000589	1·14
$1\frac{1}{4}$ in. × $\frac{1}{4}$ in. copper strip (see Fig. 4)	(1) original	0·000452	1·00
	(2) bright	0·000370	0·904
	(3) black (glossy)	0·000524	1·08
1 in. × $\frac{1}{4}$ in. aluminium strip (see Fig. 5) ..	(1) original	0·000355	1·00
	(2) black (glossy)	0·000441	1·115
	(3) black (dull)	0·000500	1·119
	(4) special dull black	0·000541	1·24

TABLE 3.

Bar	Breadth and thickness (or diameter)	Perimeter p	log p	h	log h
		cm			
Aluminium (round)	$\frac{1}{2}$ in.	3·99	0·601	0·000605	$\bar{4}$·7818
Copper (round)	$\frac{3}{4}$ in.	5·98	0·777	0·000580	$\bar{4}$·763
Aluminium (rectangular)	1 in. × $\frac{1}{4}$ in.	6·31	0·803	0·000557	$\bar{4}$·746
Aluminium (round)	$\frac{7}{8}$ in.	6·97	0·844	0·000552	$\bar{4}$·742
Aluminium (rectangular)	$1\frac{1}{2}$ in. × $\frac{3}{8}$ in.	9·52	0·979	0·000529	$\bar{4}$·7235
Aluminium (rectangular)	2 in. × $\frac{3}{8}$ in.	12·07	1·082	0·000499	$\bar{4}$·698
Copper (round)	$1\frac{3}{4}$ in.	13·95	1·146	0·000510	$\bar{4}$·708
Aluminium (rectangular)	$3\frac{1}{4}$ in. × $\frac{1}{2}$ in.	18·94	1·277	0·000488	$\bar{4}$·688
Aluminium (rectangular)	4 in. × $\frac{1}{2}$ in.	22·9	1·360	0·000483	$\bar{4}$·684

majority of the values for both round and flat bars whether copper or aluminium lie very much closer to the line. It follows from this that an approximate relation between h and p is

$$h = 0{\cdot}000732/p^{0{\cdot}140} \quad . \quad . \quad . \quad . \quad (5)$$

where p is the perimeter (in cm) of the bar whether of circular or rectangular cross-section, and h is the mean total heat emission (radiation and convection) in watts per cm² of exposed surface for 1 deg. C. of tempera-

on the mean emissivity in the case of conductors falling within the range covered is not as great as might have been expected. Thus the heat emitted under the same conditions of surface conditions and temperature difference from a bar 2 cm diameter, as compared with one of 4 cm, is

$$2^{0{\cdot}140} = 1{\cdot}102$$

If, as has been suggested, the emissivity varied inversely as the square root of the diameter, the effect

of halving the diameter would be to increase the emission by 41 per cent, i.e. four times the increase indicated by the empirical formula derived from this series of experimental results. It would not be safe, however, to assume that this formula remains valid for sizes of bars outside the range covered by the experimental determinations, nor, in the case of flat bars, for relative dimensions of breadth and thickness differing very widely from those investigated, which are those normally adopted for bare conductors in engineering practice.

Current-Carrying Capacity of Bare Conductors.

Assuming the validity of the formula within the range of sizes covered, the evaluation of tables of maximum permissible current for round or flat conductors can be deduced from the dimensions of the

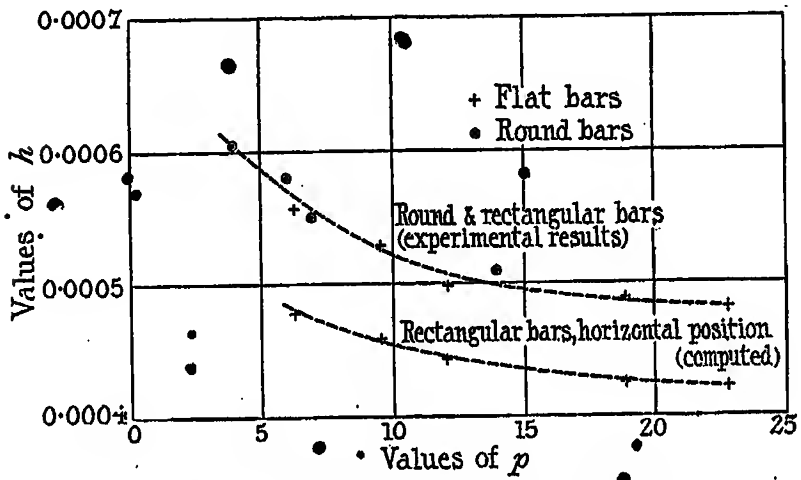

Fig. 6.—Emissivity of round and flat bars; general curve.

cross-section, the resistivity and temperature coefficient, for any given value of temperature excess.

Let p = perimeter or girth of the bar, in cm;
a = cross-section in cm^2;
ρ = resistivity of the metal in microhms per cm cube at 20° C.;
α = temperature coefficient of the latter;
I = current in amperes after stable conditions have been attained; and
θ = temperature excess of the surface of the metal above that of the surrounding air (supposed to be at 20° C.).

If H is the total amount of heat (expressed in electrical measure) generated by the current per cm run of conductor, we have

$$H = \frac{I^2(1 + \alpha\theta)p10^{-6}}{a} \quad . \quad . \quad . \quad . \quad (6)$$

and for the total amount of heat emitted per cm run we have

$$H = \frac{p \times 0 \cdot 000732 \times \theta^{5/4}}{p \times 0 \cdot 140} \quad . \quad . \quad . \quad . \quad (7)$$

whence $$I = 27 \cdot 0p^{0 \cdot 430}\sqrt{a}\sqrt{\left\{\frac{\theta^{5/4}}{(1 + \alpha\theta)\rho}\right\}} \quad . \quad . \quad (8)$$

As an overall check the formula was compared with results obtained by the direct method, i.e. by passing a steady current through lengths of conductors of various size and measuring the final temperature-rise. As an example, the ⅞ in. (2·22 cm) round aluminium bar coated with dull black paint (ordinary quality) reached a final temperature-rise of 38·5 deg. C. above that of the surrounding air when carrying 620 amperes. By the use of the formula and taking $\alpha = 0 \cdot 0039$, $\rho = 2 \cdot 84$ microhms per cm cube, $a = 3 \cdot 87$ cm^2, $p = 6 \cdot 97$ cm, and $\theta = 38 \cdot 5$, we should obtain

$$I = 27 \cdot 0 \times 6 \cdot 97^{0 \cdot 430}\sqrt{\left\{\frac{3 \cdot 87 \times 38 \cdot 5^{5/4}}{(1 + 38 \cdot 5 \times 0 \cdot 0039)2 \cdot 84}\right\}}$$
$$= 664.$$

This value must be reduced by 8 per cent since the bar was coated with ordinary dull black paint. We therefore obtain $I = 664 \times 0 \cdot 92 = 612$ amperes, a

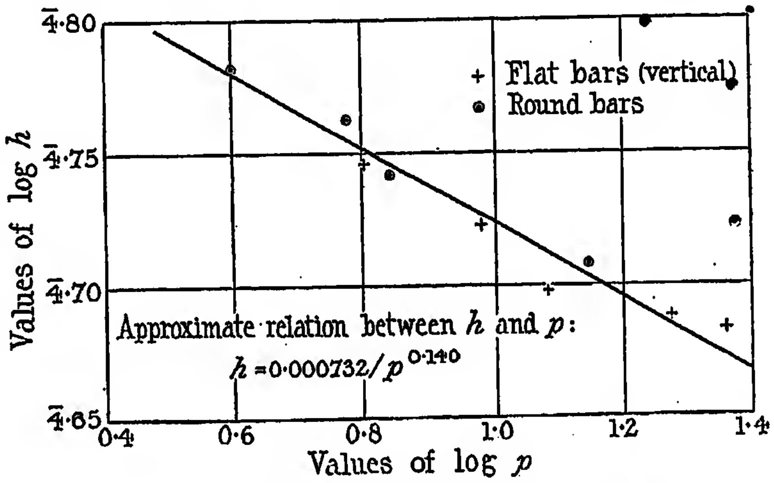

Fig. 7.—Emissivity of round and flat bars; general curve (logarithmic).

difference of 1·3 per cent from the value of 620 amperes obtained by direct experiment. Similar tests were made with other sizes and the results obtained were in close agreement, any slight difference being easily accounted for by unavoidable variations in the surface conditions of individual bars.

Calculation of Tables of Maximum Permissible Current.

For the calculation of tables of maximum permissible current for bare copper and aluminium conductors of the standard sizes given in the suggested B.E.S.A. Specification C.A. (E.L.) 5701, we proceed as follows:—

Starting with the general formula (8) we have

$$I = p^{0 \cdot 43}\sqrt{a} \times 27 \cdot 0\sqrt{\left\{\frac{\theta^{5/4}}{(1 + \alpha\theta)\rho}\right\}}$$

This, as it stands, applies to single bars covered with a specially good dull black paint, and in the case of flat bars when they are placed with the longer dimension of the cross-section vertical. The specification allows a temperature-rise of 30 deg. C. and a maximum surrounding air temperature of 40° C. The formula can therefore be further simplified by substitution of the appropriate values for θ and ρ.

Since $\theta = 30$, $\theta^{5/4} = 70 \cdot 2$.

For the terms involving ρ we have:—

(1) *Copper.*—Taking the resistivity of copper as

1·724 microhms per cm cube at 20° C., then at 40° C. $\rho = 1{\cdot}724(1 + 0{\cdot}0039 \times 20) = 1{\cdot}860$, and $(1 + \alpha\theta)\rho = 2{\cdot}070$.

The permissible current for these conditions is therefore given by the formulæ:

$$I = 157p^{0\cdot43}\sqrt{a}, \text{ for flat bars} \quad . \quad . \quad (9)$$

$$I = 264a^{0\cdot715}, \text{ for round bars.} \quad . \quad . \quad (10)$$

(2) *Aluminium.*—Taking the resistivity of aluminium as 2·84 microhms per cm cube at 20° C., then at 40° C. $\rho = 2{\cdot}84(1 + 0{\cdot}0039 \times 20) = 3{\cdot}061$, and $(1 + \alpha\theta)\rho = 3{\cdot}419$.

The permissible current for these conditions is therefore given by the formulæ:

$$I = 122p^{0\cdot43}\sqrt{a}, \text{ for flat bars} \quad . \quad . \quad (11)$$

$$I = 211a^{0\cdot715}, \text{ for round bars.} \quad . \quad . \quad (12)$$

Special allowance must be made, (1) when the bars are unpainted, or the surface condition is different from that specified; and (2) when the lead and return conductors are near each other and there is a mutual heating effect.

Effect of surface conditions.—Where ordinary black paint has been used the current values given in the tables should be reduced by 8 to 10 per cent. For unpainted bars the reduction should be 20 to 25 per cent, according to the condition of the bars.

TABLE 4.

Correction for Skin Effect.

Diameter of bar, in.		1	1⅛	1¼	1⅜	1½	1⅝
Current reduction per cent	Copper	2	4	5	—	—	—
	Aluminium	1	1	2	3	4	5

Proximity effect.—Where two bars are run close together the current-carrying capacity is reduced because of the mutual heating effect, and this is greater when the bars are painted black than when they are left with bright metallic surfaces, as in the latter case the radiation component of the emissivity is less. The effect will obviously be greatest when two flat strips are placed side by side and parallel with each other.

Where two dull black bars of equal size were run side by side and the distance between the opposite surfaces was equal to the breadth of the bars it was found that the emissivity was 6 per cent less than when the same bar was run alone. The current carrying capacity is therefore reduced by 3 per cent.

TABLE 5.

*Current-Carrying Capacity of (1) Copper Bars, Flat, with a dull black surface.**

Dimensions: t	b	a(= bt)		Current-carrying capacity	Current density
in.	in.	sq. in.	sq. cm	amps.	amps./sq. in.
¼	1	0·250	1·614	439	1 760
	1¼	0·3125	2·02	533	1 710
	1½	0·375	2·42	623	1 664
	2	0·500	3·23	803	1 607
	2½	0·625	4·03	973	1 558
	3	0·750	4·85	1 148	1 532
	4	1·000	6·46	1 493	1 490
	5	1·250	8·06	1 820	1 456
	6	1·500	9·70	2 160	1 440
⅛	¾	0·094	0·606	227	2 420
	1	0·125	0·806	298	2 380
	1¼	0·156	1·006	362	2 320
	1½	0·1875	1·210	428	2 280
	2	0·250	1·614	553	2 210
	2½	0·3125	2·015	648	2 190
	3	0·375	2·42	802	2 130
	4	0·500	3·23	1 046	2 090
$\frac{1}{16}$	½	0·0313	0·140	92·2	2 940
	¾	0·0467	0·210	132·0	2 820
	1	0·0622	0·280	172	2 770

* For ordinary black paint the current values should be reduced by 8 per cent, and for unpainted bars by 20 to 25 per cent, according to the condition of polish of the metallic surface.

TABLE 6.

*Current-Carrying Capacity of (2) Copper Bars, Round, with a dull black surface.**

Dimensions: Diameter, d		Area of cross-section		Current-carrying capacity	Current density
in.	cm	sq. in.	sq. cm	amps.	amps./sq. in.
0·236	0·599	0·0437	0·282	109·5	2 510
¼	0·365	0·0490	0·316	118·8	2 420
$\frac{5}{16}$	0·794	0·0766	0·495	164	2 140
⅜	0·952	0·1105	0·711	212	1 920
$\frac{7}{16}$	1·111	0·1505	0·907	265	1 760
½	1·270	0·1960	1·265	322	1 645
⅝	1·587	0·307	1·980	440	1 436
¾	1·905	0·442	2·85	572	1 296
⅞	2·222	0·603	3·87	711	1 178
1	2·540	0·786	5·07	864	1 100
1⅛	2·857	0·992	6·40	1 020	1 028
1¼	3·157	1·225	7·92	1 190	970

* For ordinary black paint the current values should be reduced by 8 per cent, and for unpainted bars by 20 to 25 per cent, according to the condition of polish of the metallic surface.

If, however, the distance is increased to twice the breadth of the bar, the reduction of the emissivity is almost inappreciable and the effect on the current-carrying capacity may be neglected.

When the bars are unpainted and have polished metallic surfaces, the effect of running two bars side by side is less and may be neglected if the distance between them is not less than the breadth of the bars.

TABLE 7.

*Current-Carrying Capacity of (3) Aluminium Bars, Flat, with a dull black surface.**

Dimensions				Current-carrying capacity	Current density
t	b	$a(=bt)$			
in.	in.	sq. in.	sq. cm	amps.	amps./sq. in.
$\frac{3}{8}$	$1\frac{1}{4}$	0·469	3·022	530	1 130
	$1\frac{1}{2}$	0·563	3·630	610	1 080
	2	0·750	4·840	780	1 040
	$2\frac{1}{2}$	0·935	6·04	945	1 010
	3	1·126	7·26	1 110	985
	4	1·500	9·68	1 430	953
	5	1·875	12·10	1 750	933
	6	2·250	14·52	2 070	920
$\frac{1}{4}$	$1\frac{1}{4}$	0·312	2·02	414	1 323
	$1\frac{1}{2}$	0·375	2·42	483	1 290
	2	0·500	3·23	624	1 258
	$2\frac{1}{2}$	0·625	4·03	754	1 200
	3	0·750	4·85	890	1 187
	4	1·000	6·46	1 150	1 150
	5	1·250	8·06	1 410	1 128
$\frac{3}{16}$	1	0·188	1·21	290	1 543
	$1\frac{1}{4}$	0·234	1·51	351	1 500
	$1\frac{1}{2}$	0·282	1·82	416	1 476
	2	0·375	2·42	530	1 414
	$2\frac{1}{2}$	0·470	3·03	654	1 393
	3	0·563	3·63	768	1 367
	4	0·750	4·83	995	1 328
$\frac{1}{8}$	$\frac{3}{4}$	0·094	0·606	203	2 160
	1	0·125	0·806	255	2 040
	$1\frac{1}{4}$	0·156	1·006	281	1 800
	2	0·250	1·614	430	1 714

* For ordinary black paint the current values should be reduced by 8 per cent, and for unpainted bars by 20 to 25 per cent, according to the condition of polish of the metallic surface.

Condition of ambient air.—For the purpose of calculating the tables the cooling effect of any extraneous draught has been excluded. This would be most difficult to define; where present, however, the effect would be to increase the current-carrying capacity. Generally it may be taken that the values apply to conditions surrounding busbars within a building such as a generating station, in which the only air currents are those due to convection set up by the heated conductors.

Alternating current.—The values given are in all cases for direct current. With alternating current the effective resistance of the conductors is increased because of the "skin effect," and the current ratings must be correspondingly reduced. Calculating by means of existing formulæ † for frequencies not greater than 50 periods per second, and for round bars less than 1 inch in diameter, or of the equivalent area of cross-section in the case of flat bars, it is found that the reduction of the rating will not exceed 1 per cent. For larger bars the reductions shown in Table 4 will apply.

For flat bars of equivalent cross-section the reduction in current will not be greater than for round bars and the above values will probably be sufficently accurate for the case of flat bars.

TABLE 8.

*Current-Carrying Capacity of (4) Aluminium Bars, Round, with a dull black surface.**

Dimensions				Current-carrying capacity	Current density
Diameter, d		Area of cross-section			
in.	cm	sq. in.	sq. cm	amps.	amps./sq. in.
$\frac{1}{4}$	0·635	0·0490	0·316	92·5	1 890
$\frac{5}{16}$	0·794	0·0766	0·495	128	1 670
$\frac{3}{8}$	0·952	0·1105	0·711	166	1 510
$\frac{7}{16}$	1·111	0·1505	0·970	206	1 370
$\frac{1}{2}$	1·270	0·1960	1·265	252	1 290
$\frac{5}{8}$	1·587	0·307	1·980	343	1 120
$\frac{3}{4}$	1·905	0·442	2·85	445	1 010
$\frac{7}{8}$	2·222	0·603	3·87	555	923
1	2·540	0·786	5·07	673	856
$1\frac{1}{8}$	2·857	0·992	6·40	795	803
$1\frac{1}{4}$	3·175	1·225	7·92	927	760
$1\frac{3}{8}$	3·492	1·485	9·58	1 064	719
$1\frac{1}{2}$	3·810	1·765	11·40	1 200	682
$1\frac{5}{8}$	4·127	2·073	13·35	1 344	650

* For ordinary black paint the current values should be reduced by 8 per cent, and for unpainted bars by 20 to 25 per cent, according to the condition of polish of the metallic surface.

† See LOUIS COHEN: "Formulæ and Tables for the Calculation of Alternating-Current Problems," p. 4; also H. B. DWIGHT: "Skin Effect in Tubular and Flat Conductors," *Transactions of the American Institute of Electrical Engineers*, 1918, vol. 37, p. 1395.

A NEW NETWORK THEOREM.*

By A. ROSEN, B.Sc. (Eng.), Associate Member.

(*Paper received* 28*th April*, 1924.)

SUMMARY.

A generalized theorem is given of which the well-known three-ray star-mesh transformation is a particular case. The formula is of a simple nature, and a great saving of labour results from its use. Three examples of application of the theorem follow: (1) To find the effective conductance between two points in a complicated network; (2) to find the effect of earth admittances on the balance of a Wheatstone bridge; and (3) to simplify the capacity network in the four-wire telephone cable and obtain the effective unbalance capacity.

The star-mesh theorem as applied to a star of three rays was first given by Kennelly in 1899 † and is now well known. It may be stated as follows:—

In any network the star OA, OB, OC [Fig. 1(a)] may be

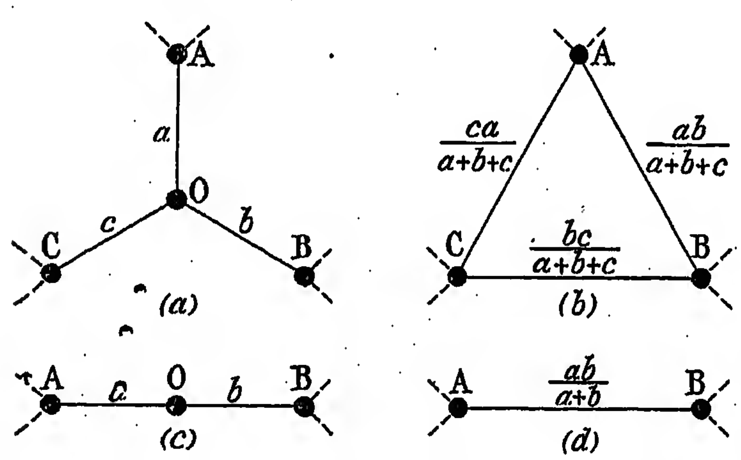

FIG. 1.—Three-ray and two-ray star-mesh transformations.

replaced by the mesh AB, BC, CA [Fig. 1(b)] without affecting the rest of the network, where, for conductance operators,

$$\mathrm{AB} = \frac{ab}{a+b+c}; \ \mathrm{BC} = \frac{bc}{a+b+c}; \ \mathrm{CA} = \frac{ca}{a+b+c}$$

Again, two conductors in series [Fig. 1(c)] may be regarded as a two-ray star OA, OB, and this is equivalent to AB in Fig. 1(d), where $\mathrm{AB} = ab/(a+b)$.

These are both particular cases of the following general theorem:—

In any network, a star of n rays, $\mathrm{OA} = a$, $\mathrm{OB} = b$, $\mathrm{OC} = c \ldots \mathrm{ON} = n$ (Fig. 2) may be replaced by a mesh of $\frac{1}{2}n(n-1)$ conductors joining every pair of the points, A, B, C, . . . N (O being eliminated), without affecting the rest of the network; then for conductance operators

$$\mathrm{AB} = \frac{ab}{\Sigma a}, \ \mathrm{BC} = \frac{bc}{\Sigma a}, \text{ etc.,}$$

where $\Sigma a = a + b + c + \ldots n.$

The following indicates the reasoning which justifies the generalization given:—

The mesh system must be symmetrical; therefore there must be a conductor joining every pair of points, i.e. a total of $\frac{1}{2}n(n-1)$ conductors in a system of the nth order where there are n rays in the star.

The expression for the value of any conductor, say AB:—

(1) must be of symmetrical form, homogeneous, and of first degree;
(2) must vanish when a or b becomes zero; and
(3) must become of one order lower as any of the other rays equals zero, and must eventually reduce to the form $ab/(a+b+c)$, the known expression for the three-ray star, and $ab/(a+b)$, the expression for the two-ray star.

Considering the form of the expression, we see from conditions (1) and (3) that it must consist of a single fraction. The denominator of the fraction can only

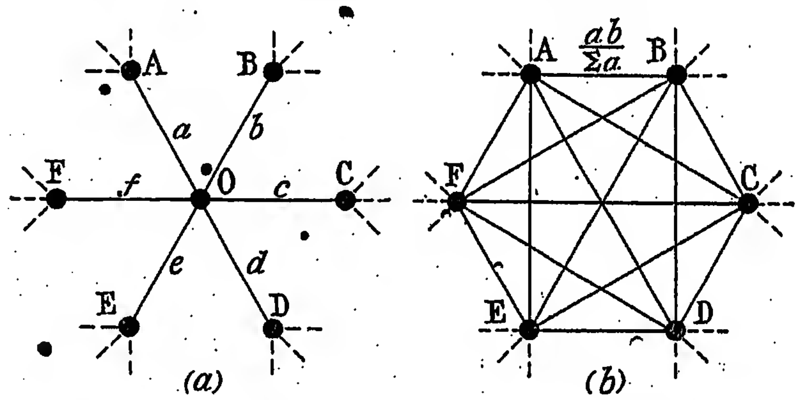

FIG. 2.—General star-mesh transformation.

be Σa to satisfy (1) and (3); the numerator from (1) can only contain terms of the second degree; and, from (2), all must contain a and b, i.e. it can only be λab, where λ is a numerical factor. By (3), λ is seen to be unity. Hence the expression $\mathrm{AB} = ab/\Sigma a$ is the only one to satisfy all conditions.

For impedance operators the result is

$$\mathrm{AB} = ab\Sigma\left(\frac{1}{a}\right), \ \mathrm{BC} = bc\Sigma\left(\frac{1}{a}\right), \text{ etc.,}$$

where $\Sigma\left(\frac{1}{a}\right) = \frac{1}{a} + \frac{1}{b} + \frac{1}{c} + \ldots \frac{1}{n}.$

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† A. E. KENNELLY: "The Equivalence of Triangles and Three-pointed Stars in Conducting Networks," *Electrical World*, 1899, vol. 34, p. 413.

This can be derived from the expression for conductances, or in a manner similar to the above; in this case condition (2) is " AB must become infinite when a or b is infinite," and condition (3) is " AB must become of one order lower as any of the other rays becomes infinite, and must eventually reduce to the form

$$ab\left(\frac{1}{a} + \frac{1}{b} + \frac{1}{c}\right)$$

the known expression for the three-ray star, and

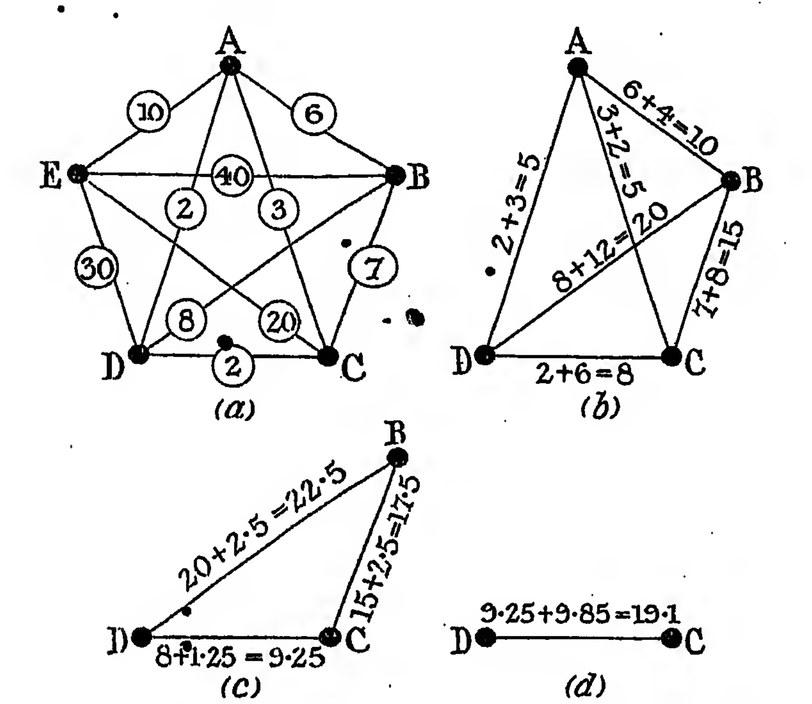

FIG. 3.—Stages in simplification of complicated network.

$(a + b)$, the expression for the two-ray star." The impedance formula is not so convenient in use on account of the frequent addition of conductors in parallel resulting from the transformations, as can be seen in the following examples.*

number of rays, and a triangular mesh can always be replaced by an equivalent star. The formulæ are, for admittances,

$$a = \text{AB} \times \text{AC}\left(\frac{1}{\text{AB}} + \frac{1}{\text{BC}} + \frac{1}{\text{CA}}\right), \text{ etc.,}$$

and for impedances,

$$a = \frac{\text{AB} \times \text{AC}}{\text{AB} + \text{BC} + \text{CA}}, \text{ etc.}$$

Applications.—The star-mesh transformation is of great assistance in simplifying the work in network problems. The case of most frequent occurrence is the three-ray star, and examples are given by Kennelly* and Butterworth.† Networks in which stars of higher order occur are necessarily more complicated, and a correspondingly greater saving in labour is obtained in applying the transformation. Three examples are given below.

(1) *To find the effective conductance between the points* C, D *in the network shown in Fig.* 3(*a*), *the values being expressed as conductances.—Step* (*i*).—Transform the four-ray star AE, BE, CE, DE into the corresponding mesh. $\Sigma a = 10 + 40 + 20 + 30 = 100$. Fig. 3(*b*) shows the resulting network with the new values of the conductors.

Step (*ii*).—Transform the three-ray star BA, CA, DA in Fig. 3(*b*) into its mesh. $\Sigma a = 10 + 5 + 5 = 20$. The resulting network is shown in Fig. 3(*c*).

Step (*iii*).—Transform the two-ray star CB, DB in Fig. 3(*c*) into its mesh. $\Sigma a = 17 \cdot 5 + 22 \cdot 5 = 40$. The final result, viz. the effective conductance across CD, is shown in Fig. 3(*d*), the value being $19 \cdot 1$.

(2) *To find the effect on the balance of a Wheatstone bridge of earth admittances located at the four corners* A, B, C, D.—Applying the four-ray transformation to

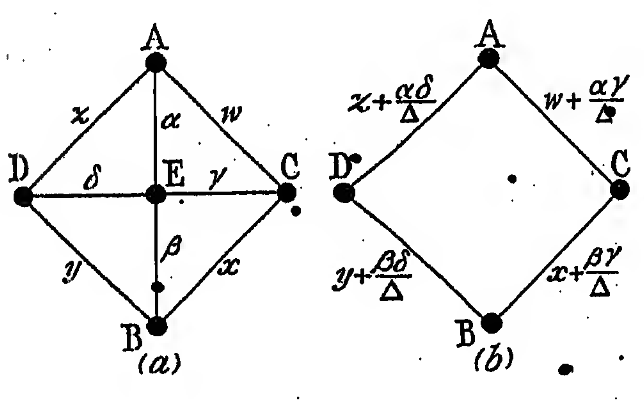

FIG. 4.—Effect of earth admittances on balance of Wheatstone bridge.

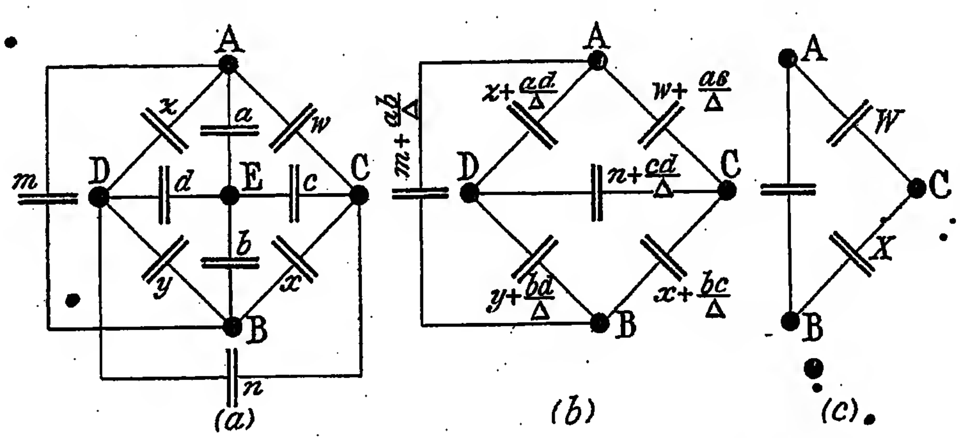

FIG. 5.—Capacity network in four-wire telephone cable.

It will be observed that since, in general, the number of mesh conductors is greater than the number of rays of the corresponding star, the theorem is not reciprocal, i.e. no mesh in which the members are arbitrary can be converted into a star. In the case of three points, however, the number of mesh conductors equals the

AE, BE, CE, DE (Fig. 4) the new condition for balance can be written down immediately as

$$\left(w + \frac{\alpha\gamma}{\Delta}\right)\left(y + \frac{\beta\delta}{\Delta}\right) = \left(x + \frac{\beta\gamma}{\Delta}\right)\left(z + \frac{\alpha\delta}{\Delta}\right)$$

where $\Delta = \alpha + \beta + \gamma + \delta$, and all quantities are expressed as admittances. The admittances across

* The impedance formula for the case of a four-ray star is given by K. KÜPFMÜLLER: "Über das Nebensprechen in mehrfachen Fernsprechkabeln und seine Verminderung," *Arch. f. Elektrotechnik* 1923, vol. 12, p. 160.

* *Loc. cit.*

† *Proceedings of the Physical Society*, 1921, vol. 34, p. 1.

AB, CD can be ignored as they shunt the source and detector and do not affect the balance.

A similar equation applies to generalized double-bridge networks. A particular case of the Wagner double bridge as applied to the Wien bridge has been worked out in detail by the author.*

(3) *To deal with the network of capacities obtained in the quad form of telephone cable in which there is a capacity between every pair of the wires* A, B, C, D, *and each wire has a capacity to the sheath* E [*Fig.* 5(*a*)].—Transforming the four-ray star AE, BE, CE, DE, the equivalent network is shown in Fig. 5(*b*). For example, to find the effective unbalance capacity between AC and BC, D being free, transform the star AD, BD, CD into its mesh AC, BC, AB. The effective value of AC is

$$W = w + \frac{ac}{\Delta} + \frac{\left(n + \frac{cd}{\Delta}\right)\left(z + \frac{ad}{\Delta}\right)}{y + z + n + \frac{d}{\Delta}(a + b + c)}$$

* "The Use of the Wien Bridge for the Measurement of the Losses in Dielectrics at High Voltages, with Special Reference to Electric Cables," *Proceedings of the Physical Society*, 1923, vol. 135, p. 249.

where $\Delta = a + b + c + d$

The effective value of BC is

$$X = x + \frac{bc}{\Delta} + \frac{\left(n + \frac{cd}{\Delta}\right)\left(y + \frac{bd}{\Delta}\right)}{y + z + n + \frac{d}{\Delta}(a + b + c)}$$

The unbalance capacity is

$$W - X = p + \frac{cu}{\Delta} + \frac{(\Delta n + cd)\left(q + \frac{du}{\Delta}\right)}{\Delta(y + z + n) + d(\Delta - d)}$$

where, in the usual notation, $p = w - x$, $q = z - y$, $u = a - b$. This result has been previously obtained by means of the usual methods, but naturally only after a great deal of labour. The application of this formula is discussed in an article on "Trunk Telephone Cables" by E. A. Beavis.*

* *Electrician*, 1924, vol. 92, p. 348.

DISCUSSION ON

"SOME RESEARCHES ON THE SAFE USE OF ELECTRICITY IN COAL MINES."*

Discussion at a Joint Meeting of the Western Centre of the Institution and the South Wales Section of the Association of Mining Electrical Engineers, at Lydney, 3 May, 1924.

Mr. I. Jones: Although the ignition tests carried out during the meeting and given in the paper were made on non-inductive circuits, they clearly show the advantage of alternating over direct current in these circumstances. In nearly all cases in actual practice, however, the circuits are inductive, and it would have been of further interest had the author carried out tests with inductive circuits, corresponding to power factors of, say, 0·6 lagging. Since the 1915 and 1916 reports on battery bell signalling by the present author and Dr. Wheeler, there is no question that considerable advance has been made in the design of signalling apparatus for underground use. The practice in the South Wales district with either the bare wire circuit (with or without pull-switches) or the insulated wire circuit with pull-switches, is to use flameproof d.c. bells, with or without relays, or a.c. bells with relays, as circumstances permit. Where a suitable a.c. lighting supply at 110 volts is available a small transformer of about 50 watts capacity with tappings on the secondary side, giving 0–25 volts in steps of 5 volts, is used for a.c. bells, together with a flameproof relay connected to the external bare wire signalling circuit. This arrangement is found very reliable in practice; the transformer having an earthed metal shield placed between the primary and secondary windings, and an a.c. bell having a small 14-volt 2-watt metal filament lamp connected across the winding. This suppresses the spark at the break and also gives a visible indication of a signal. The reactance of these transformers varies from 33 per cent to 8 per cent according to the tapping which is used; the short-circuit current is 30 amperes on the 5-volt tapping and 25 amperes on the 25-volt tapping. There is no reason why the capacity of these transformers should not be reduced to, say, 15 or 20 watts, and the reactance increased, or a small non-inductive resistance placed in the circuit, to keep down the short-circuit current to a much lower value. I should be glad to have the author's views on a.c. signalling, as this system, if made equally as safe as the d.c. system from the point of view of the flash occurring at break, is by far the best system to use in the mine. Lighting underground is at present confined to the pit bottom, and the main roadways for a comparatively short distance inbye and also engine rooms, where an electric supply is available. The voltage generally used is 110 or sometimes 50, and if the correct type of control switches, lighting fittings, and armoured cable is used, there can be no question that when properly maintained it is a sound, though

* Paper by Dr. W. M. Thornton (see page 481).

somewhat expensive, system to install. Roughly speaking, the cost of lighting underground with the present system is £2 10s. to £3 per point. The lighting in the main roadways inbye should undoubtedly be extended, as this would result in a considerable improvement in the handling of the traffic. The difficulty in the deeper mines of South Wales is to maintain the main roadways in a condition suitable for the installation of electric light, otherwise the cost of repairs and renewals would be prohibitive. Taking, for example, a main roadway of 1 000 yards in length from the pit bottom to a main parting inbye, and adopting the system of lighting advocated by the author, I take it that the method which would be adopted would be to use a main medium-tension armoured cable and to install small transformers such as were introduced by Messrs. Reyrolle. These transformers are of small capacity, and are made up in the form of straight-through joint boxes; switchgear would be used on the secondary side only, and bare wire employed for the lighting circuit in sections of, say, approximately 200 yards. This length would be nearly the maximum possible for 25-volt distribution, owing to the voltage-drop. The cost of lighting a roadway of this length would be approximately 10s. per yard. I should be glad of some further information as to the system which the author had in mind for a case of this kind.

Major E. I. David: The part of the paper in which I was particularly interested was that where the author shows what a small amount of gas is necessary to provide an inflammable mixture, when coal dust is present in large quantities. I appreciated his reference to Professor Galloway's experiments in this connection, which were commenced at Tredegar in 1895. Prof. Galloway proved most emphatically that coal dust could be ignited by a very small explosion, and would ignite most forcibly. A percentage of something under 2 per cent of methane would give an explosion every time. I think that the policy of a number of mining engineers in South Wales of using compressed air coal-cutters in dry places is the right one. Although I heartily agree with the provision of more light in every part of the pit, if this means the introduction of electricity into dry coal faces I do not think it is the right way to attack the problem. We must have a better hand lamp, rather than carry electricity to those places. I agree with Mr. Jones that it is unfortunate that the particular experiments shown by the author were not carried out with inductive circuits, because practically every circuit underground must be inductive. I find that an ordinary 25-volt a.c. bell has a resistance of 18 ohms, and an inductance of 326 mH. On a 15·5-volt circuit it takes 2 volt-amperes and has a power factor of 0·174. This means that a current of 138 mA has to be broken on the signalling wires; surely not a dangerous current, judging by the figures given in the paper. The relay which we have developed has a resistance of 323 ohms and an inductance of 1·29 H, taking a current of 30 mA at 15·5 volts and having a power factor of 0·625. When operated with a 800-ohm non-inductive shunt the signal-wire contact is absolutely sparkless. This relay will operate on lines having a resistance up to 420 ohms and, by adjustment, on a line with an insulation resistance of only 120 ohms. One type of d.c. 25-volt bell has normally a resistance of 50 ohms and a non-inductive shunt of 50 ohms across the contact. Another type has a resistance of 30 ohms, with a protective winding also of 30 ohms. Either of these can be operated with bare wires without visible sparking at the wires. With regard to lighting, I quite agree with the author's proposals. My idea of a lighting system would be a series of 100-watt to 200-watt transformers, solid compounded into the cable boxes of the main supply cables, supplying a number of 10-watt to 20-watt automobile-type lamps at, say, 25 volts. The filaments of lamps of this size would be less than 2 mm in diameter and being of tungsten would not ignite methane. The reactance of these transformers could be made such that the short-circuit current would not exceed 20 amperes. For 20 years we have been experimenting with lamps which would give instant indication of the presence of gas. If the lamp shown is a success it will be a factor in the safety of mines for many years to come. I should like to know what percentage of methane was present in Fig. 5 and what was the frequency in Fig. 6. The earth plate is an excellent one, and I should like to know if the author has any data as to its possible life.

Mr. Ll. Hughes: The paper should help to remove any existing mistrust of the application of electricity to mining work. It is necessary to find means of reducing high working costs in mines to a minimum, and we must look forward to electrical and mechanical methods of getting and transporting coal. I think that the majority of us will agree with the author that electricity is the ideal medium for conveying energy underground, but it has its limits and we must look to its application underground with a good factor of safety. The author says that if the human element of carelessness could be for ever removed there is for each possibility of electrical risk a simple and effective preventive. The Association of Mining Electrical Engineers are doing good work in removing the human element fault, by means of lectures and papers. The small percentage of electrical accidents in the South Wales coalfield confirms that statement. If we recognize the advantages of electricity for underground purposes it is our duty to make full use of the author's investigations in regard to its safe application. I agree with the author that more fixed lighting could, with advantage, be adopted for underground roadways. Most of the colliery pit bottoms are at present lit by electricity. The dispatch of full and empty trams cannot be dealt with at the same rate with ordinary safety lamps, and these improvements to transport will increase with the extension of fixed lighting, if the safe voltage can be determined. The 25-volt a.c. lighting has been installed in the pit bottom at the Treharris colliery for a number of years. The only objection to this voltage is that if a long distance has to be covered by this system the cables have to be sufficiently large to allow for the voltage drop. The author's experiments to show the effect of falls on cables installed underground should be the means of inspiring confidence in those who have any doubt of the ability of the trip-gear of a modern mining switch to deal with such conditions.

The curves on pages 486 and 487 are of interest, especially Fig. 5 which shows the influence of frequency on the ignition of methane. The results of the investigations point towards low-voltage alternating current at high frequency. The practical application of such a system to underground purposes in conjunction with existing systems, offers some problems. Schemes for districts a mile or two inbye, to provide for coal-face lighting as suggested on page 489, will call for much consideration. The statement on page 490 that the space above the oil must be thoroughly ventilated, does not agree with the design of the best type of mining switch in use to-day, in which the space above the oil is not ventilated. This space should be as little as possible, and where possible all spaces should be filled solid with compound. Referring to the earthing system described on page 490, I prefer the earthing clamp to be above the surface of the ground so that it can be inspected easily.

Mr. C. Lewis: I was rather disappointed with the experiment in connection with the miner's lamp in the gas chamber. If it had been carried out more slowly one could have obtained a better idea of the "caps" at various percentages of gas. As a matter of fact the lamp went out all at once. The author advocates high-frequency alternating current for lighting, and I should like to know what minimum frequency should be applied and what maximum frequency would be practical. The author appears to be prejudiced against bitumen cable; why does he say that bitumen cables should be prohibited?

Prof. W. M. Thornton (*in reply*): In reply to Mr. Jones, non-inductive circuits were used for three reasons. First, the influence of self-induction was worked out in 1910 for direct currents and again in the investigation on signalling bells. The influence of added inductance on ignition can be predicted in the case of direct currents once that for non-inductive circuits is known. It is not so well-defined in the case of alternating currents on account of the difficulty of breaking a circuit at a given point in the wave, and to obtain certainty as to the maximum voltage conditions at the moment of break when working with alternating currents it is necessary to use in these researches circuits that are non-inductive. Secondly, by so doing the outside limit of current is found; inductance always lowers it. Thirdly, the singular variations in the curves expressing the experimental results are complicated by inductance. For road-lighting a cable at medium pressure with small straight-through transformers would be the most convenient and economical. For face-lighting it might be better to transform at a gate end and carry 25 volts or less inbye for lighting at 150 frequency. Details of this are under consideration.

In reply to Major David, the essential feature of a safe circuit is a low time-constant. If the inductance is relatively high the resistance in series with it must also be increased. In every case the effect of inductance on ignition can be counteracted by shunts across the magnet windings. The question of better lighting at the face as a means of relieving any sense of uncertainty as to the state of things from moment to moment can in my opinion be dealt with best by a combination of the portable electric lamp and a low-tension cable, to which it may be flexibly connected by a safety interlocking attachment.

I agree with Mr. Hughes that an entirely satisfactory method of carrying electricity far inbye for coal-face lighting will call for much more investigation before it can be adopted. All that the work described in the paper does is to indicate possible lines by which the solution may be reached.

Mr. Lewis is, I think, under some misapprehension as to the test with the "dropper" type of oil safety-lamp in the gas chamber. The essential point of that lamp is that it goes out, or nearly so, before any percentage capable of forming a visible cap when the flame is high could be formed. The lamp gives warning that 2½ per cent of gas is present without any lowering of the wick, so that men can continue in full work feeling sure that full warning will be given when it is necessary to leave the place on account of gas. With regard to bitumen cables, they give off, when overheated, large quantities of methane, hydrogen and sulphuretted hydrogen, all inflammable gases, and they are, or were, rather subject to water faults on direct-current systems.

THE SHAPE OF POLE-SHOE REQUIRED TO PRODUCE A SINUSOIDAL DISTRIBUTION OF AIR-GAP FLUX DENSITY.*

By B. HAGUE, M.Sc., Associate Member.

(*Paper first received 29th April, and in final form 18th July, 1924.*)

SUMMARY.

Considerable interest has recently been shown in the complete elimination of all harmonics from the induced E.M.F. wave-form of an alternator. The methods usually employed in practice for the purification of the wave-shape fall into two classes: (*a*) in which certain harmonics are removed by proper choice of the characteristics of the armature winding, and (*b*) in which an endeavour is made to attain the desired end by producing a sinusoidally distributed flux round the air-gap. The object of the present paper is to give the theory of a commonly used method of the second class, in which the reluctance of the gap from point to point is adjusted to the value proper to the sinusoidal flux by shaping the pole-face to give a gap of varying length, longer at the tip than at the centre of the pole. The problem is solved for the case of a smooth-core armature, or for one in which the slots have been closed by means of magnetic wedges, such as would be used in a wave-form standard. Flat and circular armatures with any number of poles are dealt with, the shape of the pole-shoes and the permeance of the gap being determined in each case. The paper concludes with a numerical example illustrating the theory given in the text.

INTRODUCTION.

In discussing the elementary theory of the alternator it is usual to assume that the magnetic field in which the armature conductors are situated is distributed round the air-gap according to a sine law, so that the wave-form of the electromotive force induced in the armature winding may be sinusoidal. Since the use of impure wave-forms in alternating-current circuits gives rise to a number of technical troubles, the sine-wave alternator represents an ideal to which modern design practice is tending to attain. Indeed, the permissible variation of the voltage wave from the sine form is often stated in specifications for alternators, and an endeavour is now being made to set up a criterion by which the purity of the wave-form can logically be judged. The subject of the purity of the voltage wave of alternators has recently been considerably studied in connection with the important problem of the interference between supply networks and neighbouring telephone circuits.

In connection with the telephone interference problem it has been suggested that a small alternator might be designed to give an exact sine wave of terminal voltage, the machine being intended for laboratory use as a reference standard. Such a wave-form standard would embody all the means known to the designer to suppress all harmonics from the voltage. To this end, a smooth core with a distributed winding would be used, the pole-shoes being empirically shaped so that the flux distribution is approximately sinusoidal. Machines of a similar type have already been constructed for purposes of measurements in telephonic research.

Whether the alternator under construction is for use in ordinary engineering practice or for some special purpose such as that just mentioned, there are numerous methods available to the designer in his endeavour to secure a pure wave-form. Among these are the following:—

(1) Distribution of the armature winding in such a way as to cut out certain harmonics by the reduction of winding factors to zero. Alteration of the phase-spread or the coil-span, interlinking of the phases, the use of wave windings, and other similar devices may be employed. Unless the distribution of the gap flux is sinusoidal, it is not possible to remove all harmonics by alteration of the characteristics of the winding alone.

(2) Skewing of the armature slots or of the pole-shoes.

(3) The use of closed slots or of slots filled at the mouth with a wedge of magnetic material. In small machines slots are dispensed with entirely and a smooth core is used.

(4) Application of a system of poles which will produce a sinusoidally distributed magnetic field. Two methods are used in practice. In the first the axial width of the pole-face is so adjusted that with an air-gap of constant length an approximately sinusoidal distribution is produced.* In the second, the axial width of the pole-shoe is constant but the face of the shoe is shaped to give an air-gap longer at the pole-tip than at the pole-centre, the intention being again to produce a sine wave of flux density. This device is very commonly used for improving the flux distribution, the shoe being shaped empirically.

It is the object of the present paper to examine theoretically the last-named method, i.e. to find what shape would be given to the air-gap in a salient-pole dynamo so that the flux shall be distributed sinusoidally over the armature surface.

To solve the problem by simple mathematical methods it is necessary to lay down certain fundamental conditions, which can now be briefly stated:—

(*a*) The normal distribution of field strength over the surface of the armature core is postulated to be sinusoidal.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

* W. T. MACCALL: "Alternating-current Electrical Engineering" (1923), p. 172.

(*b*) The armature surface is supposed to be smooth, so that the flux distribution is steady.

(*c*) The iron parts are assumed to have infinite permeability, so that both the armature core and the pole-face can be taken as equipotential surfaces.

Two cases will be considered :—

(i) Where the armature has a plane surface ; and

(ii) Where the surface is a right circular cylinder.

As will be shown at a later stage, multipolar machines approximate closely to case (i). To simplify still further the details of the problem the machine is supposed to have a very great axial length, attention being confined to a portion of unit length situated at a considerable distance from the ends of the machine. The distribution of the magnetic field in the portion under consideration is then sensibly two-dimensional.

In either case the method to be adopted is the same. With the given armature surface and the assumed flux distribution over it, an endeavour is made to find the natural system of equipotential surfaces due to these given conditions. A pole-shoe coinciding with any one of these equipotentials will then give the desired flux distribution on the core. Briefly, the process consists in finding a function Ω specifying the magnetic potential at points external to the armature core. If $\partial\nu$ be an element of length in a given direction the magnetic field-strength in that direction is, from the well-known definition of potential, given by

$$H_\nu = -\frac{\partial\Omega}{\partial\nu}$$

Ω must be chosen so that H_ν has specified values on the armature surface. The choice of a suitable form for Ω is suggested by experience and is determined by the nature of the surfaces bounding the field. Ω must, however, satisfy Laplace's equation of continuity, expressed in suitable co-ordinates. The following sections will show the procedure applicable to the present problem.

Armature with Plane Face.

In Fig. 1 let XOX be the plane surface of the infinitely permeable armature core. Further, let the surface be at zero magnetic potential and let the magnetic field strength normal to the surface be

$$H = H_1 \sin\frac{\pi x}{X} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where X represents the pole-pitch. It is now required to find the resulting magnetic potential, Ω, at a point P external to the plane core.

It is easy to show from a consideration of the continuity of the flux passing P that the potential must satisfy Laplace's partial differential equation

$$\frac{\partial^2\Omega}{\partial x^2} + \frac{\partial^2\Omega}{\partial y^2} = 0 \quad . \quad . \quad . \quad . \quad (2a)$$

Moreover, since XOX is an equipotential surface the entire magnetic field strength on it must be normal to the surface and equal to the assumed field. The potential must be such, therefore, that the boundary conditions

$$\left(-\frac{\partial\Omega}{\partial y}\right)_{y=0} = H_1 \sin\frac{\pi x}{X} \quad . \quad . \quad (2b)$$

and
$$\left(-\frac{\partial\Omega}{\partial x}\right)_{y=0} = 0 \quad . \quad . \quad . \quad . \quad . \quad (2c)$$

are simultaneously satisfied.

From these boundary conditions experience indicates that the appropriate form for the potential is

$$\Omega = YH_1 \sin px$$

wherein Y is a function of y only and p is a constant coefficient to be determined.

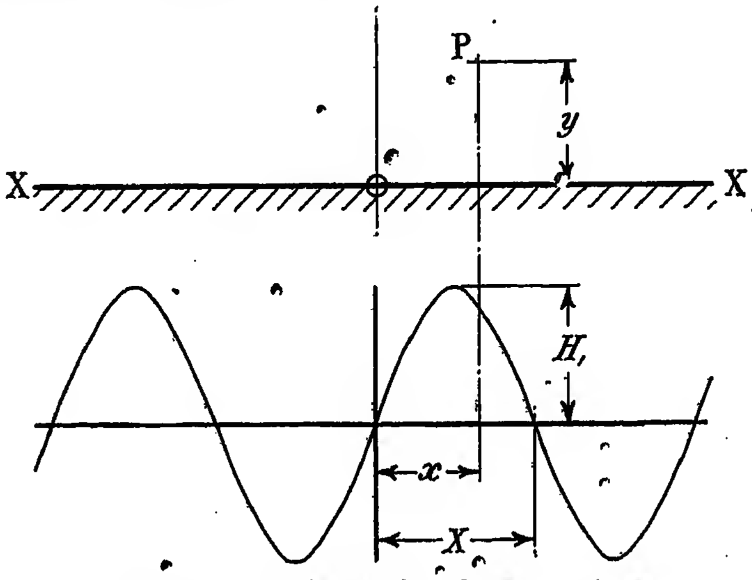

Fig. 1.—Co-ordinates for plane armature.

Inserting the assumed form for Ω in Equation (2*a*) gives

$$\frac{d^2Y}{dy^2} = p^2 Y$$

the solution of which is

$$Y = A\epsilon^{py} + B\epsilon^{-py}$$

A and B being constants. Hence

$$\Omega = H_1(A\epsilon^{py} + B\epsilon^{-py}) \sin px \quad . \quad . \quad (3)$$

Differentiating Equation (3) with respect to y and then making $y = 0$ gives

$$\left(-\frac{\partial\Omega}{\partial y}\right)_{y=0} = -H_1 p(A - B)\sin px = H_1 \sin\frac{\pi x}{X}$$

[from Equation (2*b*)]

Comparison of coefficients makes

$$p = \frac{\pi}{X}$$

and
$$p(A - B) = -1$$

whence
$$A = B - \frac{X}{\pi}$$

Next differentiating Equation (3) with regard to x, making $y = 0$, and comparing with Equation (2*c*), gives, on insertion of $p = \pi/X$ and $A = B - (X/\pi)$,

$$\frac{\pi}{H_1 X}\left(2B - \frac{X}{\pi}\right)\cos\frac{\pi x}{X} = 0$$

From this and the preceding relation,

$$A = -\frac{X}{2\pi} \quad \text{and} \quad B = \frac{X}{2\pi}$$

Finally, putting these values of A and B in Equation (3), we get

$$\Omega = -H_1\frac{X}{\pi}\sin\frac{\pi x}{X}\sinh\frac{\pi y}{X} \quad . \quad . \quad . \quad (4)$$

Natural equipotentials and lines of force.—On an equipotential Ω is constant; writing $C = -\pi\Omega/H_1X$ as a parameter, we get

$$\sin\frac{\pi x}{X}\sinh\frac{\pi y}{X} = C \quad . \quad . \quad . \quad . \quad (5a)$$

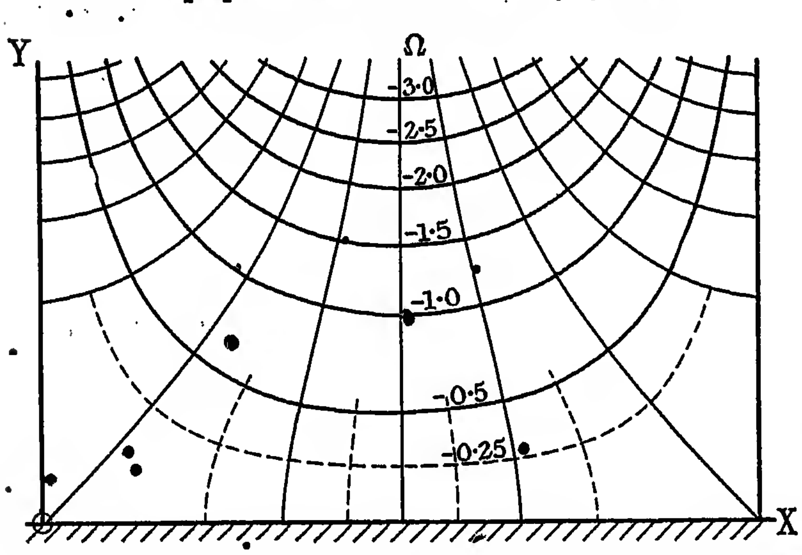

Fig. 2.—Equipotentials and lines of force near plane armature plotted from Equations (5*a*) and (5*b*).

as the equation to the equipotentials natural to the sinusoidal field distribution. These are plotted from $x = 0$ to $x = X$ in Fig. 2 for various positive values of C, i.e. for negative values of Ω.* The equipotentials facing this portion of the plane armature are thus south poles, as is otherwise obvious when it is remembered that flux is leaving the armature (H positive) between 0 and X.

From Equation (5*a*) we obtain by differentiation

$$\frac{dy}{dx} = -\tanh\frac{\pi y}{X}\cot\frac{\pi x}{X}$$

The lines of force cut the equipotentials at right angles, so that the slope on them must satisfy the equation

$$\frac{dx}{dy} = \tanh\frac{\pi y}{X}\cot\frac{\pi x}{X}$$

which on integration gives

$$\cos\frac{\pi x}{X}\cosh\frac{\pi y}{X} = D \quad . \quad . \quad . \quad . \quad (5b)$$

as the equation to the lines of force, D being a parameter. These are also plotted in Fig. 2.

Shape of pole-shoes.—In Fig. 2 the ordinates through the points 0 and $\frac{1}{2}X$ are axes of symmetry. Choosing a definite numerical value equal to C, let the equipotential surfaces given by Equation (5*a*) be traced for $+ C$, giving south poles, and for $- C$, giving north poles. This is done in Fig. 3. It is now clear that a system of alternate north and south poles having the shapes of these equipotential surfaces and having magnetic potentials determined by $\mp C$ will give rise to a sinusoidal field along the armature surface XOX.

It is obvious from the shape of these poles that the leakage between successive north and south poles will be infinitely great and that there is, moreover, no provision for a magnetizing coil to maintain the poles at their appropriate potentials. These objections and their practical significance will be referred to later in dealing with the more important case of a machine with a circular armature core.

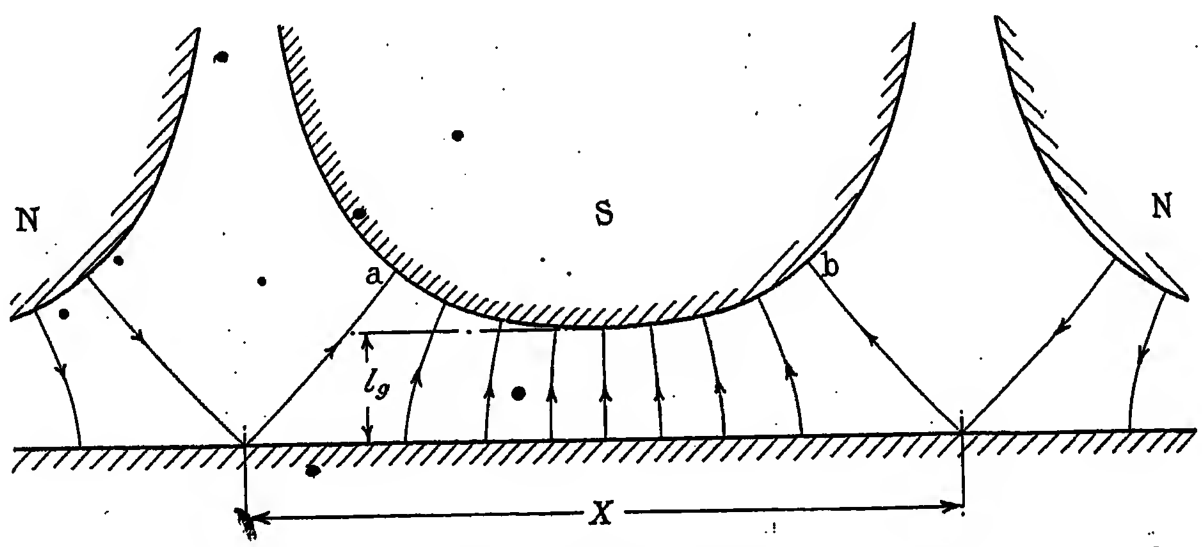

Fig. 3.—Pole-shoe form required to produce sinusoidal flux distribution on the surface of a plane armature. Useful arc of pole is "ab."

Permeance.—Assuming the poles to have the ideal shape indicated in Fig. 3, it is of interest to examine the permeance of the air-gap field, this being emitted by the arc "ab" of the pole.

Since the field at the armature face is given by $H = H_1 \sin(\pi x/X)$, the flux per pole is

$$F = \int_0^X H dx = \frac{2}{\pi}XH_1 \text{ per cm axial length}$$

* For a similar diagram see R. Rüdenberg: "Über die Verteilung der magnetischen Induktion in Dynamoankern und die Berechnung von Hysterese- und Wirbelstromverlusten," *Elektrotechnische Zeitschrift*, 1906, vol. 27, p. 109. The matter is also dealt with by F. Emde: "Sinusrelief und Tangensrelief in der Elektrotechnik" (1924), p. 93.

Let the chosen equipotential pass through a point of which the co-ordinates are $(\frac{1}{2}X, l_g)$; then from Equation (5a) the appropriate value of the potential of the shoe will be given numerically by $(H_1X/\pi)\sinh(\pi l_g/X) = \Omega'$ say. Then if α = least gap length/pole-pitch $= l_g/X$, the permeance of the gap field per unit axial length is

$$\mathbf{P} = \frac{F}{\Omega'} = \frac{2}{\sinh \alpha\pi} \quad . \quad . \quad . \quad . \quad (6)$$

which is plotted in Fig. 4.

It is important to compare the permeance given by Equation (6) with that calculated by Carter * for a

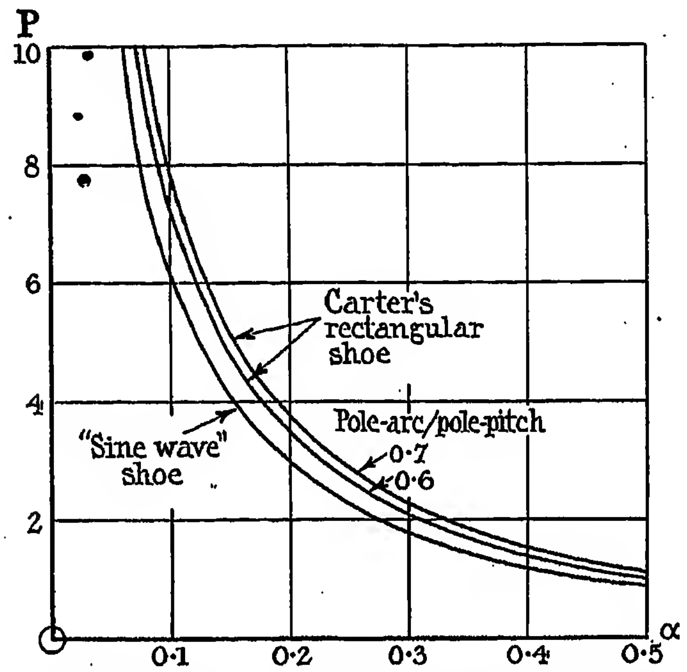

FIG. 4.—Permeance of air-gap between pole and armature. The ordinate gives **P**, the permeance per pole for 1 cm axial length; the abscissa is the ratio α = least gap length/pole-pitch.

plane armature opposite which is placed a system of alternate north and south poles with infinitely deep rectangular shoes. Carter shows that the permeance may be expressed as

$$\mathbf{P} = \frac{b}{l_g} + 2\lambda$$

where b is the pole-arc,

l_g the gap length, and

$$\lambda = \frac{2}{\pi}\left[\frac{c}{l_g}\arctan\frac{l_g}{c} + \frac{1}{2}\log_e\left\{\frac{1}{4}\left(1+\frac{c^2}{l_g^2}\right)\right\}\right]$$

in which $c = \frac{1}{2}(X - b)$. This expression for the permeance has been plotted for comparison in Fig. 4 for two values of pole-arc/pole-pitch, corresponding to certain proportions of pole used in practice. The designer will see that the adoption of the "sine-wave" shoe only results in a small loss of permeance when compared with a "rectangular" shoe having the usual practical ratio of arc to pitch.

ARMATURE WITH CIRCULAR SURFACE.

Attention will now be directed to the solution of the more practical problem in which the surface of the armature is a right circular cylinder, represented by the circle of radius a in Fig. 5. Let the circle be at zero magnetic potential so that the magnetic field is normal to it and can be represented by

$$H = H_1 \sin p\theta \quad . \quad . \quad . \quad . \quad . \quad (7)$$

p being the number of pairs of poles in the machine.

The magnetic potential at a point P at which the polar co-ordinates are (r, θ) must satisfy Laplace's equation expressed in cylindrical polars, namely

$$\frac{\partial^2\Omega}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial\Omega}{\partial r} + \frac{1}{r^2}\cdot\frac{\partial^2\Omega}{\partial\theta^2} = 0 \quad . \quad . \quad . \quad (8a)$$

In addition, Ω must be such that the normal component of field on the circle $r = a$ is the given value of H and the tangential component is zero; that is

$$\left(-\frac{\partial\Omega}{\partial r}\right)_{r=a} = H_1 \sin p\theta \quad . \quad . \quad . \quad (8b)$$

and

$$\left(-\frac{1}{r}\cdot\frac{\partial\Omega}{\partial\theta}\right)_{r=a} = 0 \quad . \quad . \quad . \quad . \quad (8c)$$

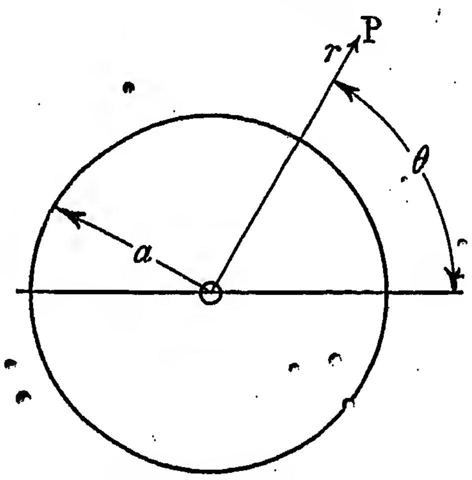

FIG. 5.—Co-ordinates for circular cylindrical armature.

To solve Equation (8a), assume that the form of Ω is

$$\Omega = R \sin n\theta$$

where R is a function of r only and n is a coefficient. Then substitution in Equation (8a) yields

$$r^2\frac{d^2R}{dr^2} + r\frac{dR}{dr} - n^2R = 0$$

This equation is of the homogeneous form, the trial solution of which is $R = r^m$. Inserting this gives

$$m^2 - n^2 = 0,$$

or

$$m = \pm n$$

Thus the value of R is

$$R = Ar^n + Br^{-n}$$

A and B being constants to be found. Hence

$$\Omega = (Ar^n + Br^{-n})\sin n\theta \quad . \quad . \quad . \quad (9)$$

Differentiating Equation (9) with respect to r, making $r = a$ and comparing with Equation (8b), gives

$$\left(-\frac{\partial\Omega}{\partial r}\right)_{r=a} = -n(Aa^{n-1} - Ba^{-n-1})\sin n\theta = H_1 \sin p\theta$$

Comparison of coefficients shows that

$$\left.\begin{aligned} n &= p \\ H_1 &= -n(Aa^{n-1} - Ba^{-n-1}) \end{aligned}\right\} \quad . \quad . \quad (10a)$$

* F. W. CARTER: "Note on Air-gap and Interpolar Induction," *Journal I.E.E.*, 1900, vol. 29, p. 925.

Again, differentiating Equation (9) with respect to θ, making $r = a$ and using Equation (8c), we get

$$\left(-\frac{\partial\Omega}{r\partial\Omega}\right)_{r=a} = -n(Aa^{n-1} + Ba^{-n-1})\cos n\theta = 0$$

from which

$$A = -Ba^{-2n} \quad . \quad . \quad . \quad . \quad . \quad (10b)$$

potential Ω is constant; writing $C = -2p\Omega/(H_1a^{p+1})$ as a parameter we get

$$\left(\frac{r^p}{a^{2p}} - \frac{1}{r^p}\right)\sin p\theta = C \quad . \quad . \quad . \quad (12a)$$

as the equation to the natural equipotentials.* These have been plotted in Fig. 6 for two cases, namely when

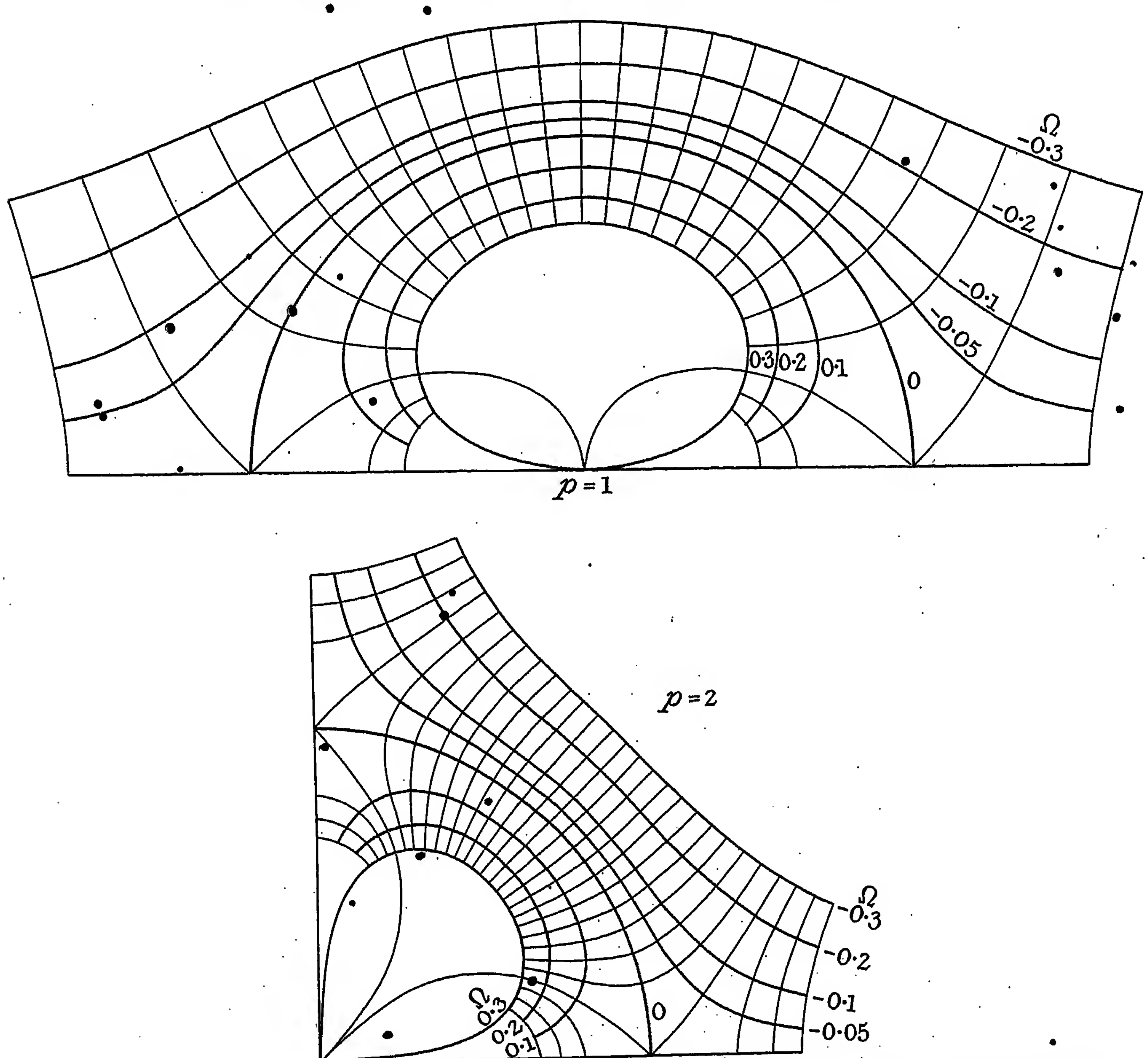

FIG. 6.—Equipotentials and lines of force near circular cylindrical armature plotted from Equations (12a) and (12b) for $p = 1$ and $p = 2$.

Solving Equations (10a) and (10b) makes

$$A = -\frac{H_1}{2p}a^{-p+1} \quad \text{and} \quad B = \frac{H_1}{2p}a^{p+1}$$

which on insertion in Equation (9) gives for the magnetic potential,

$$\Omega = -\frac{H_1a^{p+1}}{2p}\left(\frac{r^p}{a^{2p}} - \frac{1}{r^p}\right)\sin p\theta \quad . \quad . \quad (11)$$

Natural equipotentials and lines of force.—On an equi-

$p = 1$ and $p = 2$. In this diagram it has been assumed that $a = 1$ unit and that $H_1 = 1$. In each case one pole has been drawn; the diagram must be repeated

* The equation to the equipotentials has been given by Dr. J. F. H. DOUGLAS, *Transactions of the American Institute of Electrical Engineers*, 1915, vol. 34, p. 1067, in the case of a two-pole machine. Putting $p = 1$ in Equation (12a) gives $\left(\frac{r}{a^2} - \frac{1}{r}\right)\sin\theta = C$; transforming from polar to rectangular co-ordinates by writing $r^2 = x^2 + y^2$, $\sin\theta = \frac{y}{r}$, $Ca = \frac{y}{a} - \frac{ay}{x^2 + y^2}$ is the equation to the equipotentials in a two-pole machine, as is shown by Dr. Douglas. In the case of multi-polar machines it is simpler to retain the polar form of the expressions.

$2p$ times round the circle, the sign of Ω marked thereon being reversed at each repetition.

Differentiating Equation (12a) gives

$$\frac{d\theta}{dr} = -\frac{r^{2p} + a^{2p}}{r^{2p} - a^{2p}} \times \frac{\tan p\theta}{r}$$

Since the lines of force cut the equipotentials at right

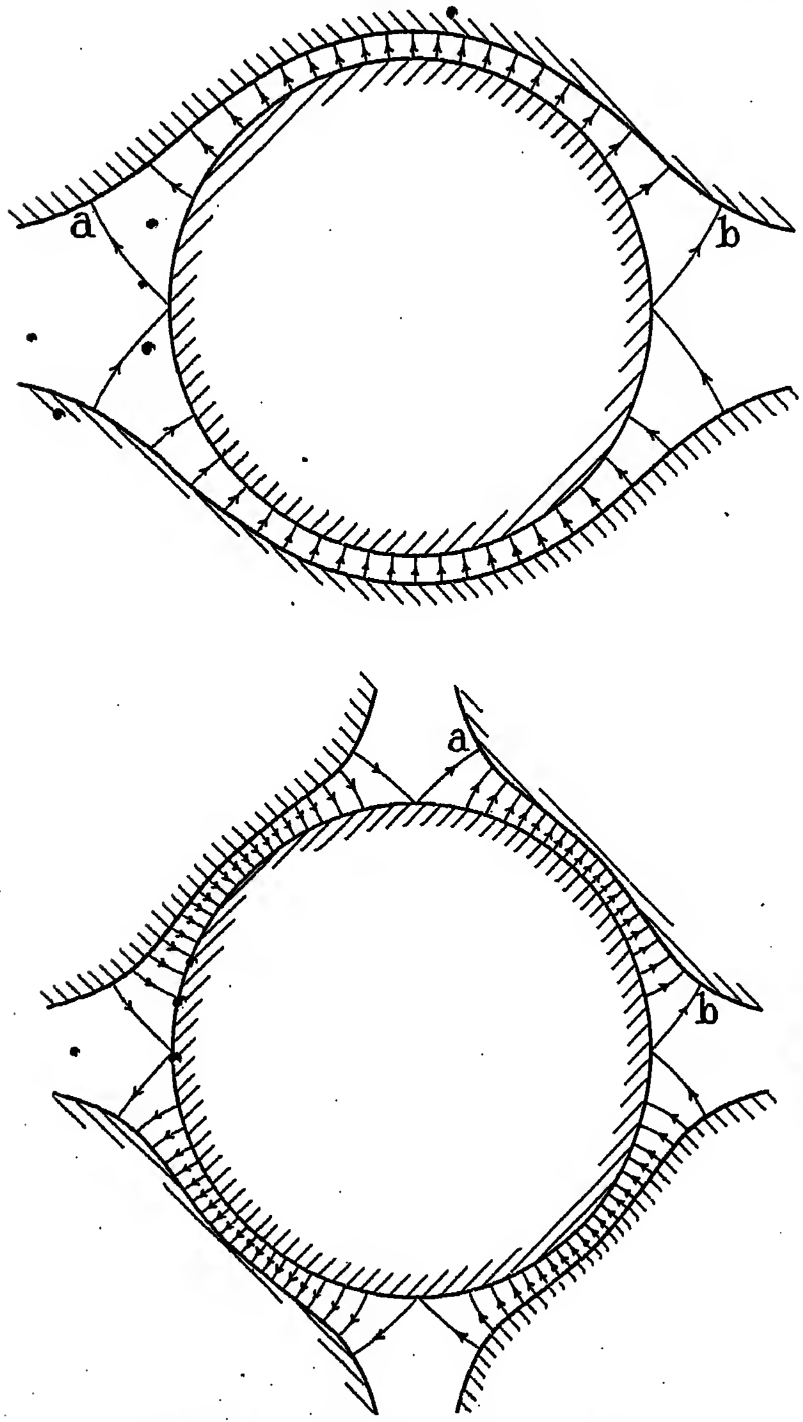

FIG. 7.—Pole-shoe form required to produce sinusoidal flux distribution on the surface of a circular cylindrical armature for two-pole and four-pole, smooth-core machines with external poles. Useful arc of pole is "ab."

angles the slope $d\theta/dr$ on them must satisfy the equation

$$\frac{1}{r^2} \cdot \frac{dr}{d\theta} = \frac{r^{2p} + a^{2p}}{r^{2p} - a^{2p}} \times \frac{\tan p\theta}{r}$$

which on integration gives

$$\left(\frac{r^p}{a^{2p}} + \frac{1}{r^p}\right) \cos p\theta = D \quad . \quad . \quad . \quad (12b)$$

as the equation to the lines of force. These have been plotted in Fig. 6 in such a way that the flux per pole is divided into 20 tubes of force of equal strength.

Shape of pole-shoes.—In the same way as before, the pole-shoes should be chosen to coincide with the equipotential surfaces of alternate south and north polarity defined by $+ C$ and $- C$ in Equation (12a). Typical instances are adapted from Fig. 6 and are shown in Figs. 7 and 8. Fig. 7 shows two-pole and four-pole machines with external poles; Fig. 8, on the other hand, depicts the corresponding internal-pole machines. In both diagrams the gap lines of force are indicated.

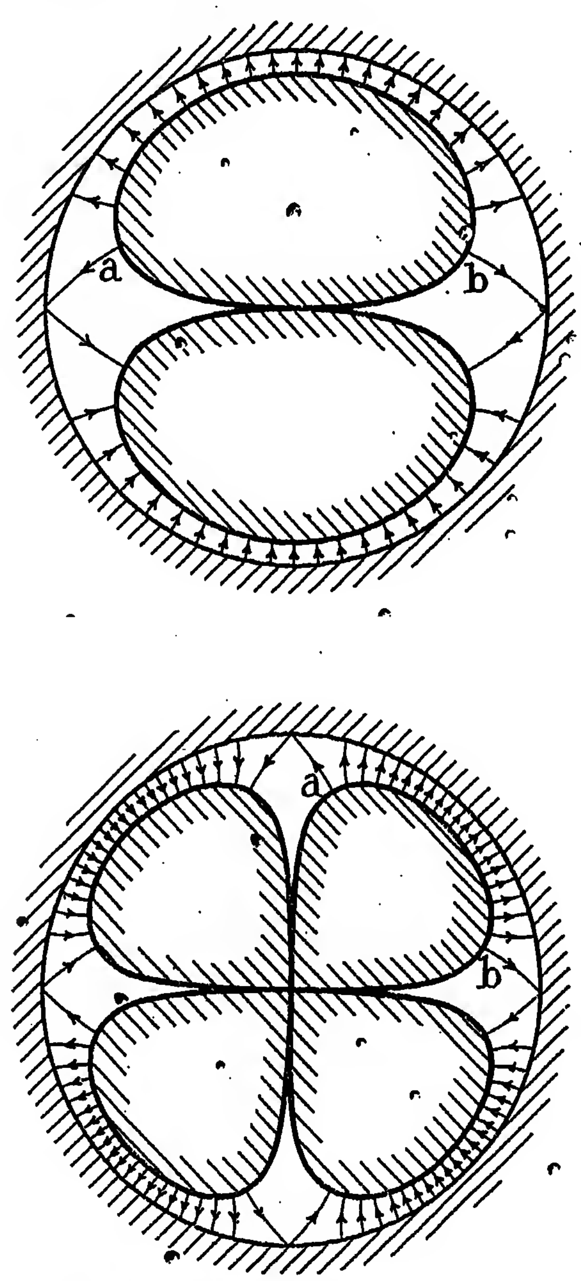

FIG. 8.—Pole-shoe form required to produce sinusoidal flux distribution on the surface of a circular cylindrical armature for two-pole and four-pole, smooth-core machines with internal poles. Useful arc of pole is "ab."

It is interesting at this stage to note an important practical fact. In a sine-wave generator the armature winding is bound upon the surface of the core; hence the conductors lie upon the core at a mean radius greater than a—assuming a machine with external poles. Inspection of Equation (11) shows that $\partial\Omega/\partial r$ is proportional to $\sin p\theta$ for *any* value of r, i.e. on any circle concentric with the core the radial component of the field is still sinusoidally distributed round the

periphery. The conductors will thus still remain in a sinusoidal field even though they are above the core surface. A similar argument and result can easily be seen to apply to the flat-core problem, as an inspection of Equation (4) will show, since $\partial\Omega/\partial y$ is proportional to sin $(\pi x/X)$ for all values of y.

The shapes of poles shown in Figs. 7 and 8 cannot be completely realized in practice, owing to the fact that a practical pole possesses a core upon which a magnetizing coil is wound. This core is provided with a shaped shoe facing the armature. The results of this paper can be very approximately utilized in practice by arranging that the shoe face is cut to fit the arc marked ab of the chosen equipotential. Since the rest of the pole does not coincide with the remainder of the equipotential, the interpolar leakage will be considerably altered, and with it to some extent the distribution of the flux influence of the magnetizing coil and the core of the pole on the distribution of the air-gap flux will be small if the breadth of the core is not great in comparison with that of the shoe. The field in the gap is then screened by the shoe from the stray field of the magnetizing coil and from the effects of the modified interpolar leakage. In these circumstances the results of this paper should apply with a high degree of accuracy, and any remaining discrepancy could be compensated by the artifice shown in Fig. 9 for the case of a two-pole machine. Cut out the pole-shoe to conform to two of the theoretical equipotentials and attach it to a small pole-core in the manner just suggested. Since the iron of the shoe has a high permeability, both surfaces of the shoe will be approximately equipotentials and will not be much influenced by stray fields from the main coil. Now put on the tips of the shoe an auxiliary winding

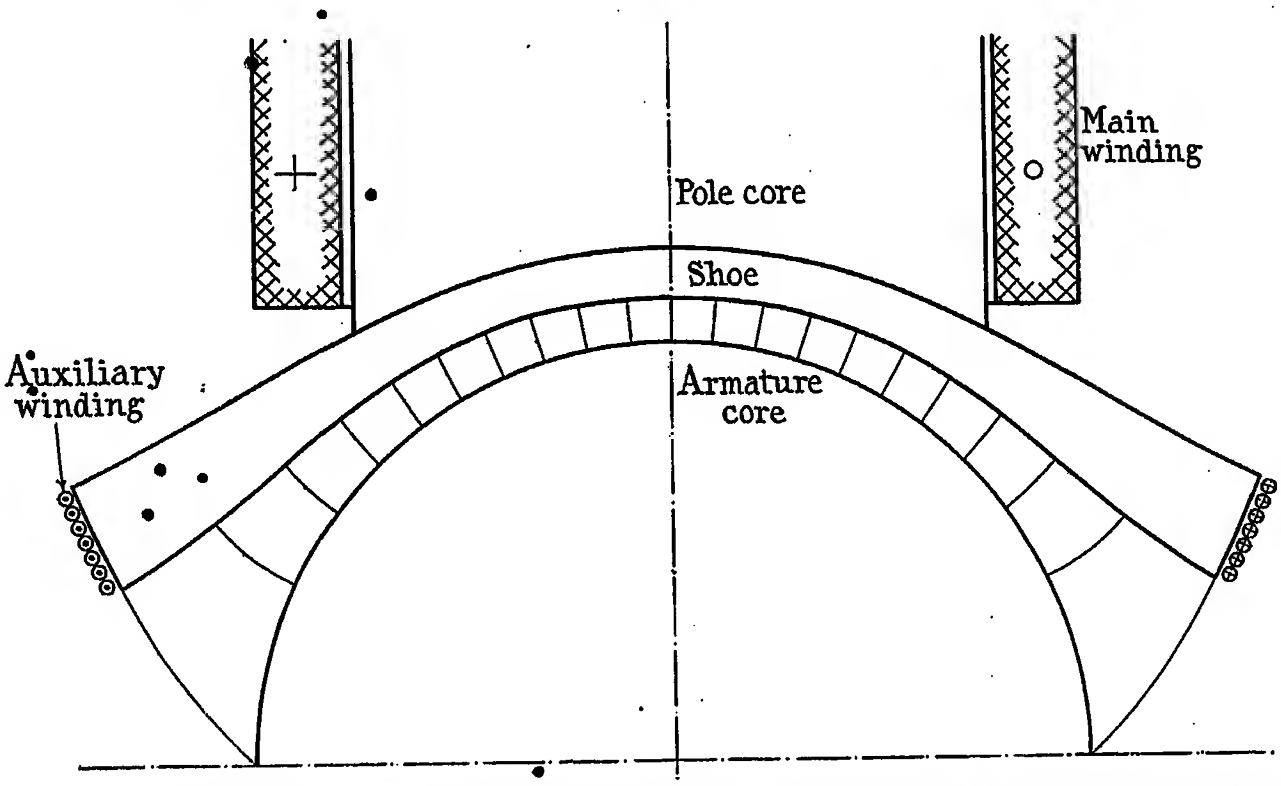

FIG. 9.—Detail of pole-shoe in two-pole machine, showing auxiliary winding arranged to compensate for the effects of the main field winding and the pole-core on the air-gap flux distribution.

which leaves the corners of the shoe. To restore the sinusoidal flux distribution on the armature core the pole-tips would require to be slightly reshaped. The precise amount of shaping could, in any given case, be found by a process of trial and error using any suitable experimental or graphical method.*

Mr. S. Neville has pointed out to the author that the opposing the main winding and such that the drop of magnetic potential along the edge of the shoe is equal to the difference of potential between the chosen equipotentials. This device might be necessary in wave-form standards where absolute purity of flux distribution is desired.

Permeance.—The gap permeance when the shoe has the ideal shape is easily found. Let F be the flux per pole, then

$$F = \int_0^{\pi/p} H a d\theta = H_1 a \int_0^{\pi/p} \sin p\theta d\theta = \frac{2H_1 a}{p}.$$

When $\theta = \pi/(2p)$ and the pole-shoe is formed by the equipotential passing through a point at a radius $r = b$ the numerical value of the potential thereon is, from Equation (11),

$$\Omega' = \frac{H_1 a^{p+1}}{2p}\left(\frac{b^p}{a^{2p}} - \frac{1}{b^p}\right) \doteq \frac{H_1 a}{2p} \cdot \frac{(b^{2p} - a^{2p})}{a^p b^p}.$$

* The Kirchhoff current method is one of the most convenient experimental methods for the purpose. Two electrodes, one shaped to represent the pole-shoe and the other the armature, are clamped upon a sheet of tinfoil and are maintained at a constant difference of potential. The equipotential lines in the sheet correspond to the required magnetic equipotentials, and are easily plotted by means of potential contacts and a galvanometer. The method has been used by Dr. Douglas in the paper cited. Another convenient method makes use of electrodes of appropriate forms immersed in an electrolyte, the equipotential lines being plotted out. This method, apparently originally used by W. G. ADAMS (*Proceedings of the Royal Society*, 1875, vol. 23, p. 280) has been employed by a number of investigators in Germany and America; it has recently been employed by A. A. AHMED (*Journal I.E.E.*, 1924, vol. 62, p. 801) with considerable improvements and has been put on a sound experimental basis as a result of his work.

The best graphical process is that of Richardson. This depends on the fact that the lines of force and the equipotentials in the space between given bounding surfaces divide up that space into a series of curvilinear squares. These can be sketched in freehand and the shape of each adjusted by eye until correct, using a process of trial and error. The method is much used by German and other Continental designers and writers, who always refer to it as Lehmann's method.

The permeance per unit axial length is thus

$$\mathbf{P} = \frac{F}{\Omega'} = \frac{4a^p b^p}{(b^{2p} - a^{2p})} = \frac{4a^p b^p}{(b^p - a^p)(b^p + a^p)}$$

The minimum air-gap is $b - a$; if $b > a$ the machine has external poles, if $b < a$ the poles are internal. This result can be put into a more convenient form; let β = radius at pole-centre/radius of armature $= b/a$, then

$$\mathbf{P} = \frac{4\beta^p}{(1 + \beta^p)(1 - \beta^p)} \text{ numerically} \quad . \quad (13)$$

from which the shape of the pole-face in any given case can be approximately found. To illustrate this the following numerical example will be of service. Take the case of a two-pole, smooth-core, sine-wave alternator with external poles, the radius of the armature core being $a = 15$ cm. If the minimum length of the air-gap be 1 cm, the radius to the pole-centre will be $b = 16$ cm. Let the maximum flux density be $H_1 = 6\,000$ lines per cm^2, so that the flux per pole for 1 cm axial length is

$$2H_1 a = 2 \times 6\,000 \times 15 = 180 \text{ kilolines.}$$

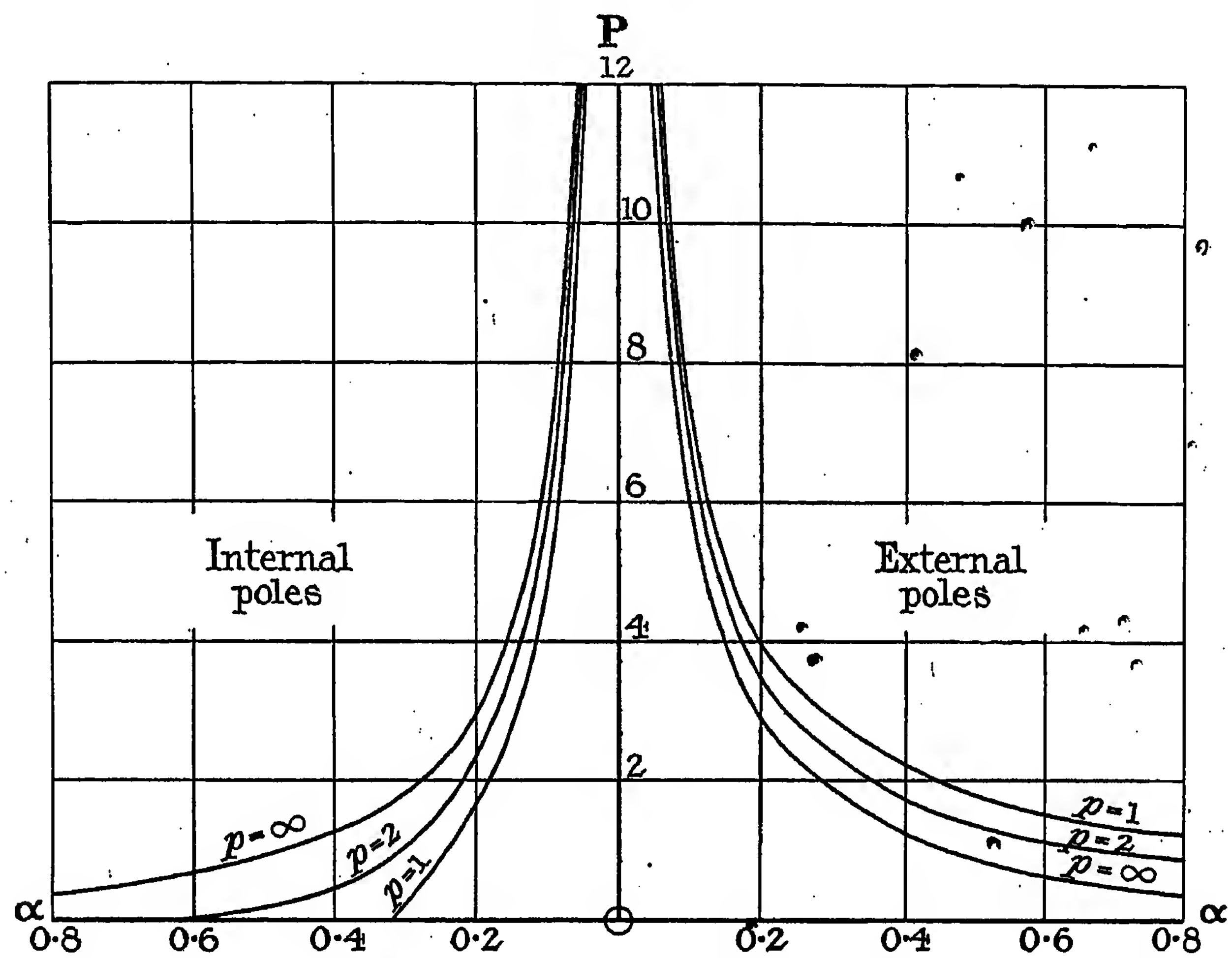

FIG. 10.—Permeance of air-gap between pole and armature. The ordinate gives P, the numerical value of the permeance per pole for 1 cm axial length; the abscissa is the ratio α = least gap length/pole-pitch, the latter being measured at the armature surface.

By a simple change of variable these results can be compared with the permeance curve for a flat armature. Thus

$$\frac{p}{\pi}(\beta - 1) = \frac{p}{\pi}\left(\frac{b}{a} - 1\right) = \frac{(b-a)}{\pi a/p} = \frac{\text{minimum gap}}{\text{pole-pitch}} = \alpha$$

Equation (13) is plotted in Fig. 10 to a base of α, the curve of Fig. 4 for a flat armature being included for comparison. It will be seen that multipolar machines tend to approximate closely to the result found for a flat armature.

CONCLUSION.

The formulæ developed in the paper and the curves plotted therefrom will provide the designer with data

Referring to Equation (11) and putting $p = 1$, $r = b$, $\theta = \frac{1}{2}\pi$ gives for the potential of the shoe

$$\Omega' = \frac{H_1}{2b}(b-a)(b+a) = \frac{6\,000}{2 \times 16} \times 1 \times 31$$
$$= 5\,810 \text{ C.G.S. units.}$$

Inserting this value in Equation (12*a*) makes

$$C = -\frac{2\Omega'}{H_1 a^2} = -\frac{2 \times 5\,810}{6\,000 \times 15^2} = -0{\cdot}0086$$

so that the equation to the pole-face is

$$\left(\frac{r}{225} - \frac{1}{r}\right)\sin\theta = -0{\cdot}0086$$

in which $r > 16$. By choosing values of r, θ can readily

be calculated and the curve set out on polar co-ordinate paper. To determine the useful arc of the curve—the arc "ab" of Fig. 7—it is necessary also to set out the critical line of force emanating from the armature surface at the point $r = a$, $\theta = 0$. Putting this in Equation (12*b*) gives $D = 2/a$, so that the equation to the critical line limiting the arc is

$$(225 + r^2) \cos \theta = 30r.$$

The ampere-turns required for the gap are

$$\Omega'/0 \cdot 4\pi = 5\,810/0 \cdot 4\pi = 4\,640$$

and the permeance per cm axial length is

$$\mathbf{P} = 180\,000/5\,810 = 31.$$

In conclusion the author wishes to thank Professor G. W. O. Howe and Mr. S. Neville for their valuable advice and criticisms during the preparation of the paper.

SOME NOTES ON INSULATING PAPERS.

By A. I. MACNAUGHTON, B.Sc., STUDENT.

(ABSTRACT *of paper read before the Scottish Students' Section, 14th December*, 1923.)

INTRODUCTION.

During recent years considerable attention has been given to insulating papers, and the author hopes that the following notes may prove of value, as no clear appreciation of the possibilities and limitations of such papers can be obtained without a knowledge of what paper is and how it is made.

Paper is usually defined to be " a deposit of vegetable fibres from aqueous suspension," and these fibres belong to one or other of chemical groups known as " cellulose."

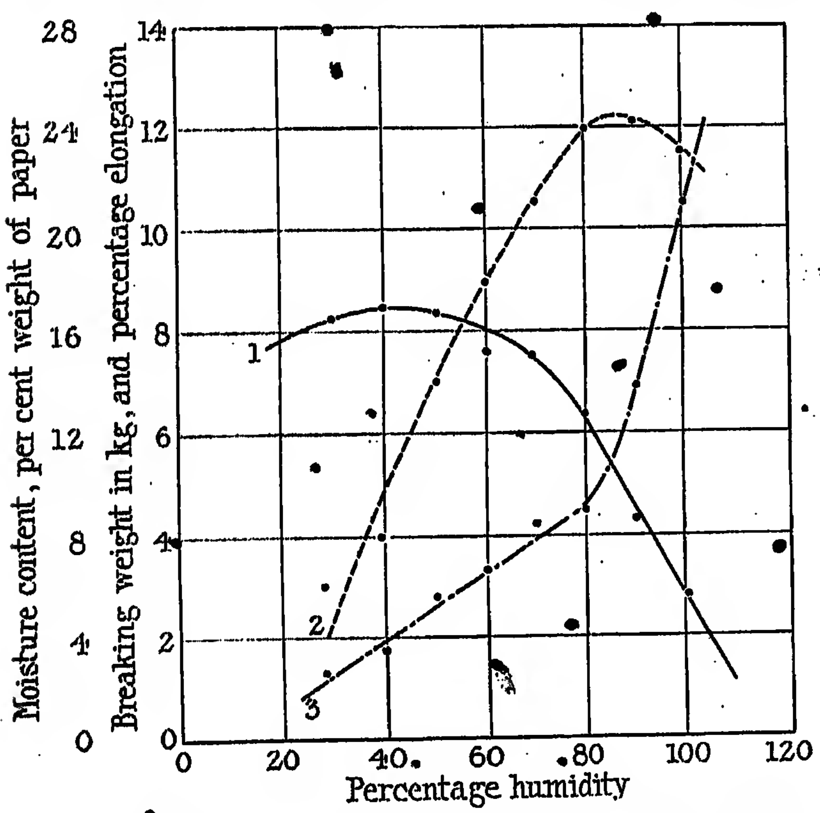

FIG. 1.—Relation between humidity, moisture and strength.

Only two celluloses are considered here: (*a*) Normal cellulose, which is contained in cotton, linen and hemp, and (*b*) cellulose obtained from other vegetable origins, which is more highly oxidized than that already referred to. There are many forms of this latter class, but the exact constitutional differences are not understood, though, proportional to their degree of oxidation, they are more liable to attacks from acids and atmospheric conditions. Another property common to all types of cellulcse is "water of condition," and this varies for each cellulcse. This water content varies directly as the humidity for any constant temperature, and it greatly affects the tensile strength (see Fig. 1).

MANUFACTURE OF PAPER.

In the preliminary treatment all impurities have to be removed from the raw material, which may be rags, jute bagging, old manilla ropes, etc. They are picked

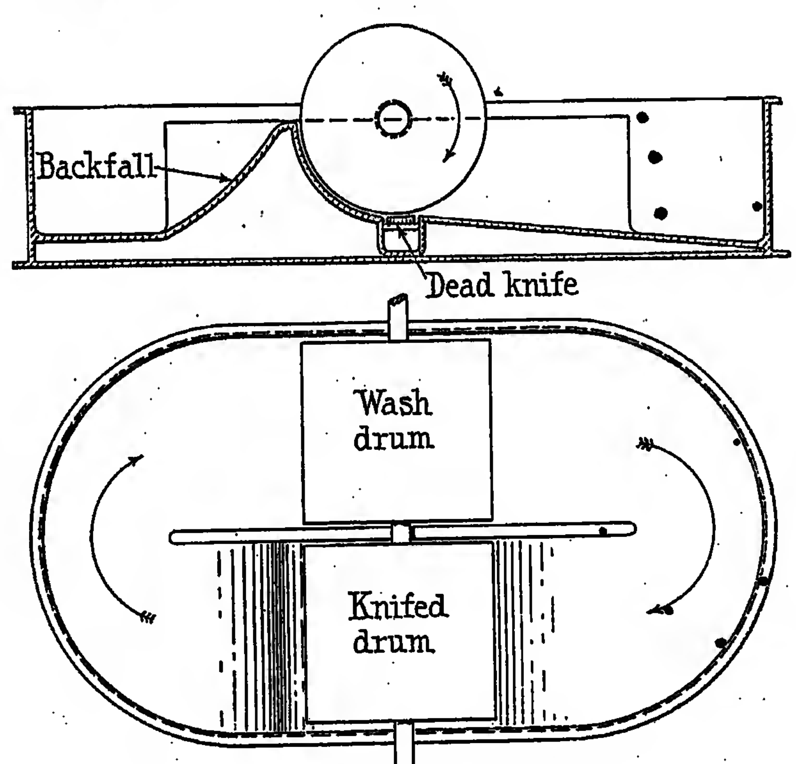

FIG. 2.—Diagram of hollander.

by hand to remove all pieces of metal, etc., after which the material is dusted and partially disintegrated by cutting in special machines. After this treatment it is passed into large rotating boilers where it is boiled with an alkaline solution for a period of about 6–10 hours under a steam pressure of 10–60 lb./sq. in.

Wood pulps are prepared in the same way, i.e. the

"soda" and "sulphate" group of pulps are prepared by digesting the wood with an alkaline lye of caustic soda, and the "sulphite" pulps by boiling with an acid solution of hydrogen sulphites of calcium or magnesium, the difference being that while in the former group the resin is unaffected, in the latter it is dissolved.

When the wood—or rags, as the case may be—is completely digested, the liquor is run off and the pulp washed with a copious supply of water.

After this preliminary treatment the pulp has to be resolved into its elementary fibres, and the fibres themselves cut to lengths of from 4 to 1·5 mm. This is carried out in a "breaker" or "hollander" (Fig. 2), which consists essentially of an oval trough containing two revolving drums, one on either side. One drum is fitted with longitudinal blades which cut the fibres to their desired length, while the other, a framework covered with fine wire cloth, carries off the dirty water, clean water being added to the trough until the pulp, or "half-stuff," is thoroughly cleaned. The "half-stuff" is then fed into the "beater," which is similar to a "breaker" except that it has no wash drum. Here the fibres are again cut or bruised and fibrillated, according to whether absorbent or non-absorbent paper is required. When the fibres are bruised they become coated with a slimy hydrated cellulose film. Non-absorbent paper is stronger than absorbent paper. To make the paper thoroughly non-absorbent, size must be added. This is prepared by treating melted resin with sodium carbonate and then diluting with water, the resulting solution being added to the beater. The addition of alum again precipitates the resin, which forms a coating on the paper, making it waterproof.

Paper Machine.

The only paper machine described by the author is the "Fourdrinier" paper machine.

After the pulp leaves the beaters it is led into the store tank or "stuff-chest," from which it is pumped continuously, through sand traps and strainers, until it is fed evenly on to the whole width of an endless band of wire gauze. The consistency at this point is about 1 per cent (i.e. 1 lb. of dry pulp to 99 lb. of water). The wire gauze is supported on suitable rollers and moves forward in a horizontal plane (Fig. 3), the pulp being prevented from overflowing by means of a pair of endless rubber belts which rest on, and run with, the wire. The water separates from the pulp by dropping through the wire gauze, this action being accelerated by suction boxes over which the wire is passed. The pulp, which is now wet paper, is further dried by passing between heavy rollers. The paper web, supported on an endless band of felt, is passed through two or more sets of press rollers, and then through a series of steam-heated drying cylinders, the web being maintained by the felt in close contact with the cylinders.

Thus stated, the action of the "Fourdrinier," machine is quite simple, but in practice it presents some difficulties. First, the whole wire belt has imparted to it a lateral motion termed the "shake" in order to assist to "felt" the sheet together. This shake, as it plays a very important part in determining the strength of the finished product, must be controllable both as regards frequency and travel. Secondly, the paper shrinks as it dries on being passed over the drying cylinders, and so the drying cylinders must be run at a progressively lower speed as the paper proceeds down the machine. This variation in speed must also be controllable since different papers shrink according to the materials used in their manufacture.

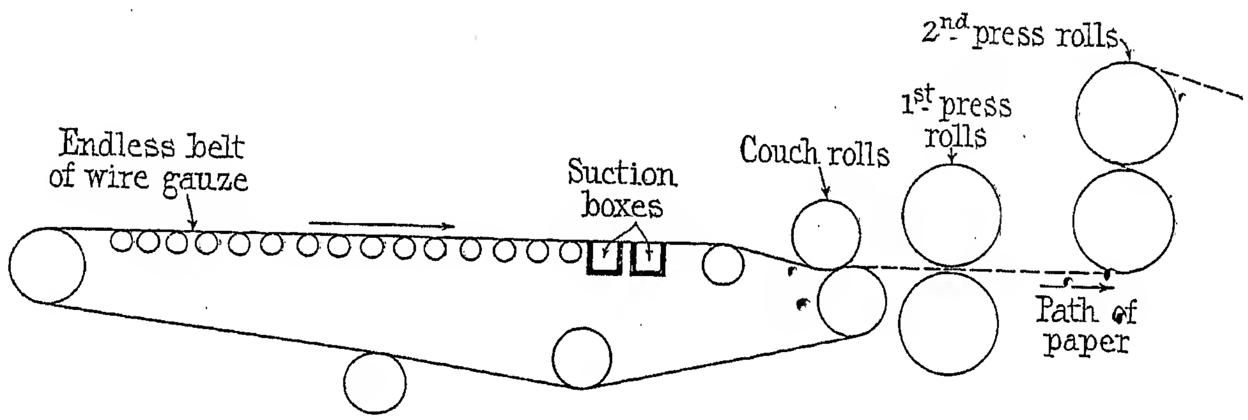

Fig. 3.—Line diagram of paper machine wire.

No matter how the pulp is cleaned, certain impurities are always present in paper. In the original paper a list of these impurities, which include (1) free acids, (2) sulphur, and (3) metals, was given, their effect on the quality of the paper was stated, and the methods used to detect and eliminate them were detailed. In addition, the physical tests to which paper can be submitted were given and described. These include: (*a*) Thickness, (*b*) tensile strength, (*c*) bursting strength, (*d*) folding, (*e*) pinholes, and (*f*) porosity. These tests are all carried out in accordance with the specification of the Electrical Research Association.

Insulating Papers.

(*a*) *General.*—For papers used for the insulation of machine slots, bolt-holes in yokes or to form cores for coil windings in transformers, where the electrical pressures between adjacent conductors are not large, mechanical strength is the determining factor, and papers made from sulphite wood pulp, and glazed, are found satisfactory. Tissue papers used for condensers must be free from pinholes and are usually made from linen

rags which are grass bleached, i.e. bleached by the sun and atmosphere.

(b) *Cable papers.*—Papers for insulating cables must be very pure, both chemically and physically, free from all metallic inclusions, and must also be able to absorb varnish, a fact which may diminish their strength. Owing to the excessive cost of manilla ropes, "composite papers" are sometimes used for this purpose and are compositions of several types of varnishes were given in the original paper.

DRY-CORE CABLES FOR TELEPHONE WORK.

These are insulated with unimpregnated paper made from manilla. In the original paper a list of clauses in the suggested Research Association type of specification

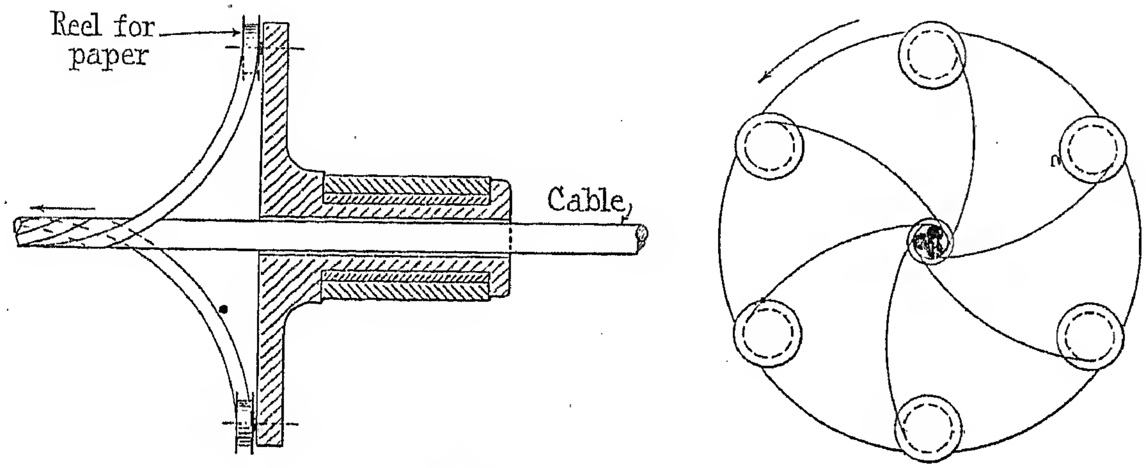

FIG. 4.—Cable-winding cage.

made from jute and soda wood. The paper is laid on to the cable by means of a "cage." This carries the paper reels (see Fig. 4), and as it revolves it wraps the paper around the cable. The cable is dried under vacuum at about 275° F. for 12–30 hours, and is then impregnated at 240° F. with varnish for 4–30 hours, after which it is led direct to the bitumen forcing machine. The

was set out. This specification is given in the *Journal* (1923, vol. 61, p. 982), and embodies the following clauses: Condition, Thickness, Density, Tensile Strength, Bursting Test, Tearing Test, Porosity, Absorption Test, Moisture Loss, Acidity and Alkalinity, Mineral Ash Test, Resinous Material, Nitrogenous Material, Metallic Particles, Flash Test and Microscopical Examination.

ELECTRIFICATION SCHEMES IN RUSSIA.

By B. L. METCALF and O. MORDUCH, Students.

(ABSTRACT *of paper read before the* NORTH-WESTERN STUDENTS' SECTION, *25th February*, 1924.)

SUMMARY.

The importance of foreign markets for the electrical industry of Great Britain and the characteristics of Russia as a prospective market for electrical goods are discussed, a brief account being given of general Russian economics.

The possibilities of electrification in Russia, and projects of various electrification schemes are then described, and an outline of results achieved and work done is included.

1. INTRODUCTION.

The future of the electrical industry in Great Britain is becoming increasingly dependent upon its export trade. It is important, therefore, that all engineers, even though they may belong to a purely technical branch of their profession, should take a broader, more open-minded, view of the problems facing their industry. The beneficial results to be obtained from research departments are now fully recognized by most of the big manufacturing concerns in this country, but in these research departments the amount of time devoted to commercial research is disproportionately small. The British electrical industry, although comparatively young, has gained an honourable place among the electrical industries of other countries, and can now safely compete anywhere with regard to the quality and wide range of its products, but the problem is how to find a regular demand for these products, a demand which will maintain the industry in a healthy state and in addition help it to expand and develop. The needs of the home market are insufficient, consequently a voluminous and permanent export trade must be built up—and this as energetically as possible if the good start that has been made is not to be lost. In line with these special considerations there is the national problem of widespread unemployment which calls for the earnest attention of all sections of the community. The need for commercial research, therefore, to discover and develop new markets, and to assist in the disposal of finished products, seems to be a very urgent one and worthy of more active attention than it has received up to the present. Due recognition must be given to the good work that has been, and is being, done in connection with Empire development, and to the attempt to create a single self-supporting unit out of the British Empire; but the results so far obtained in this direction have been inadequate, and the depression at home is still very acute. The indication is that the trade of Great Britain must continue to be world-wide and must not limit itself to any one particular region.

2. SEARCH FOR NEW MARKETS.

To attempt to find a new field for commercial development, the guiding factors are:—

(1) Large natural resources.
(2) Accessibility of these resources.
(3) Political or legal, and physical considerations.
(4) Backward state of development.

Keeping these ideas in mind, the country which presents itself most forcibly and which appears to satisfy the above considerations to a marked degree is Russia. Russia is the largest potential market in Europe, possessing enormous mineral and agricultural wealth. Yet it is practically undeveloped, as may be seen from Fig. 1. The shaded area represents the

Regions at present commercially developed.
Regions capable of development, but as yet undeveloped.

FIG. 1.

regions as yet undeveloped, but capable of development, and is seen to cover practically the whole of Russia, with the exception of a small industrial area in the extreme west, and a narrow belt following the route of the Siberian Railway. The extreme north and the plains of Siberia are incapable of development at present.

3. STATE OF ELECTRICAL INDUSTRY AND DEVELOPMENT IN 1914.

The following works existed in Russia in 1914:—

A. *Electrical machinery.**—Russian Dynamo Co.'s works in Moscow, employing 1 000 hands. Volta works in Reval, employing about 500 hands. A.E.G. (Russian) works in Riga, employing over 1 000 hands.

* The manufacture of electrical machinery in Russia was not sufficient to cover the requirements of the home market, over 60 per cent of this having to be imported from abroad. The output of the above works for 1913 was—besides other electrical machinery—14 300 dynamos and motors, with a total power capacity of 311 000 kW, making an average of about 22 kW. In the case of cable production, practically all the needs of the Russian market were covered by the output of the works named.

Siemens-Schuckert works in Petrograd, employing about 1 000 hands.

B. *Cable works.*—Union Cable works in Petrograd. Kolchooghno Cable works north of Moscow. Russian Cable and Rolling Mill Co. in Moscow (associated with the Russian Dynamo Co. and the B.T.H. Co. in England). Shamshin and Alexieff in Moscow.

C. *Power supply.*—The power supply in Russia before the war was in a very unsatisfactory state, the demand being met chiefly by a number of small stations which were for the most part privately owned.

D. *Industrial application.*—Electricity was not employed to a great extent in the Russian factories. Only some of the larger works had their machinery electrically driven, but even in these works the electric drive was far from being universally adopted.

4. Erection of New Power Stations.

The main idea underlying the plan for erection of these stations is their development parallel to the

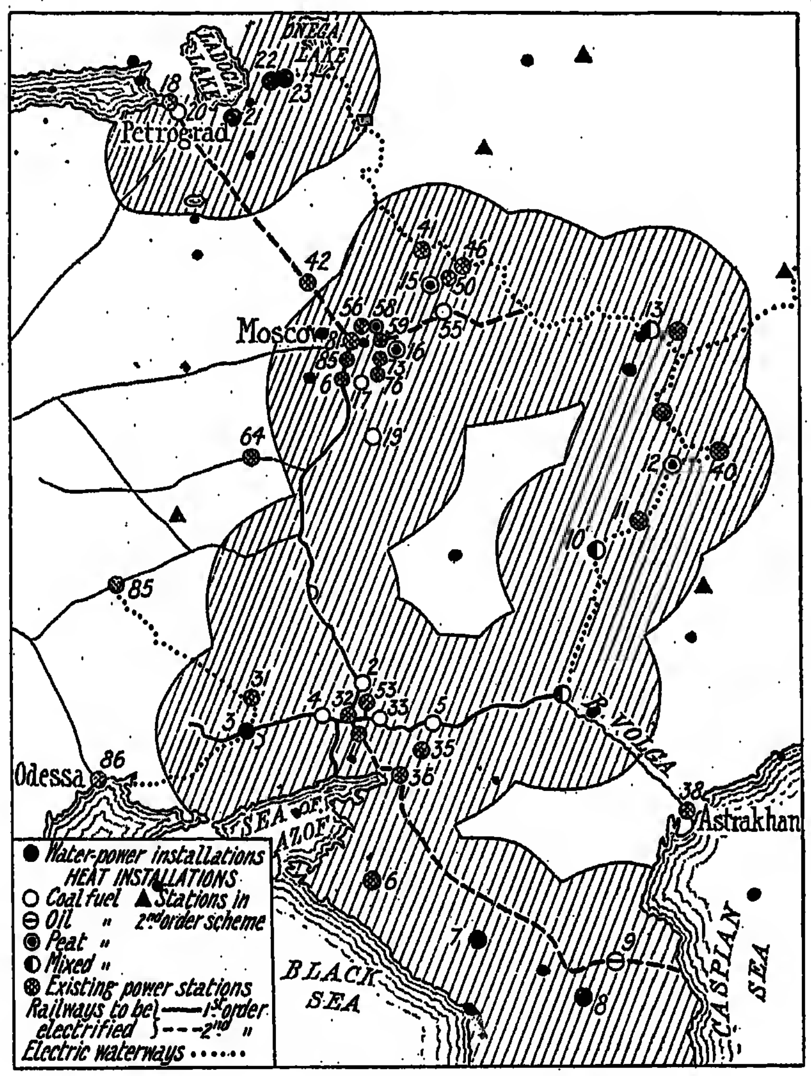

Fig. 2.—Electrification of Russia.

growth of the load. The electric load on the power stations has been steadily increasing since 1919–20, when it reached its minimum. At present the lighting load, having almost reached (on the average) its pre-war magnitude, will henceforth continue to grow rather slowly. On the other hand, the power load is as yet very much below its pre-war value, but is increasing and is expected to continue to grow rather rapidly. Accordingly, the stations are designed to deal with these existing and prospective loads. The shaded part of Fig. 2 represents the area within which the stations are to be erected. It will be seen from this map that Siberia has been left out of this scheme altogether, but that the electrification of European Russia is planned on a fairly extensive scale. The aggregate power capacity of these stations is under 2 000 000 kW, which is a comparatively modest figure, particularly so, if it is remembered that this aggregate will be reached only towards 1935. The whole of the electrification work will be divided into districts, viz. Petrograd, Moscow (Central Industrial), South-West, Ural, Caucasus, Donec Basin, Volga and Turkestan.

The following are some of the stations to be erected:—

A. *Hydro-electric stations.*

Volchov.—The ultimate capacity of this station is to be 200 000 h.p.

Svir.—Three power stations are to be erected, of a total capacity of 500 000 h.p.

Dneipr.—The maximum output of the proposed Dneipr station is to be 330 000 kW.

Water-power stations in Turkestan.—A 7 500-kW station at Troizkoe and a 27 000-kW station on the River Tchirtchik.

Ural.—(*a*) Tchoosavaia, 4 280 000 h.p. available.
(*b*) A canal contemplated between the Rivers Kama and Tobol would furnish a considerable amount of water power in the locks.

Caucasus.—Both on the Goktcha Lake and on the River Terek, 120 000 h.p. are available.

B. *Power stations working on fuel.*

Utkina Zavod.—A power station near Petrograd to be worked mainly on peat. The maximum output is to be 30 000 kW.

Shatura.—This station is situated about 70 miles south of Moscow. The ultimate capacity of the station will be 60 000 kW. This was one of the first stations to be built, and is one of the largest worked on peat.

Summary.—Thirty central stations are to be erected, with a total power capacity of 1 740 000 kW. This means an average capacity per station of about 60 000 kW.

The maximum individual capacity of any one station (the water-power station on the River Dneipr) will be 300 000 kW.

The stations may be classified as follows:—

A. *Water power.*—Ten stations, total capacity 640 000 kW.

B. *Fuel.*—Twenty stations, total capacity 1 000 000 kW.

(*a*) Coal: ten stations, total capacity	..	540 000 kW
(*b*) Oil: two stations, total capacity	..	70 000 kW
(*c*) Peat: four stations, total capacity	..	210 000 kW
(*d*) Mixed fuel: four stations, total capacity		180 000 kW

These stations are to be completed and their ultimate capacity is to be reached before 1935.

5. Railway Electrification.

The lines put down for electrification before the war were the following (see Fig. 3):—

(1) Petrograd–Oranienbaum in the north-west. The scheme included one power house, somewhere midway between Petrograd (Baltic station) and Oranienbaum, and two substations at the above places. The project was quite completed and contracts were already placed, a considerable part coming to this country. The war, however, prevented the carrying out of this scheme.

(2) Plans on a larger scale and of greater importance were made in connection with the Moscow district; there the work had been seriously started on a section of the Moscow–Kazan railway about 40 miles long, the transmission system being 11 000 volts, three-phase, and the distribution being direct current at 1 500 volts. Here, again, the war stopped the work.

(3) A scheme for an underground railway in Moscow, connecting all the main-line terminals (seven in number) and the business centre of the town was seriously considered. The principal advantage of this scheme was the possibility of running the main-line trains from one terminus to another right through the city.

(4) Other, more indefinite schemes existed for the electrification of lines from Moscow to Kursk, down south through the Crimea, as far as Tsaritzino; the Sevirnaia line (up north) and the Alexander line (to Warsaw) as far as Golitzino. On all these lines it was the intention to electrify comparatively short sectors to begin with.

Other schemes in existence were the coastal railway

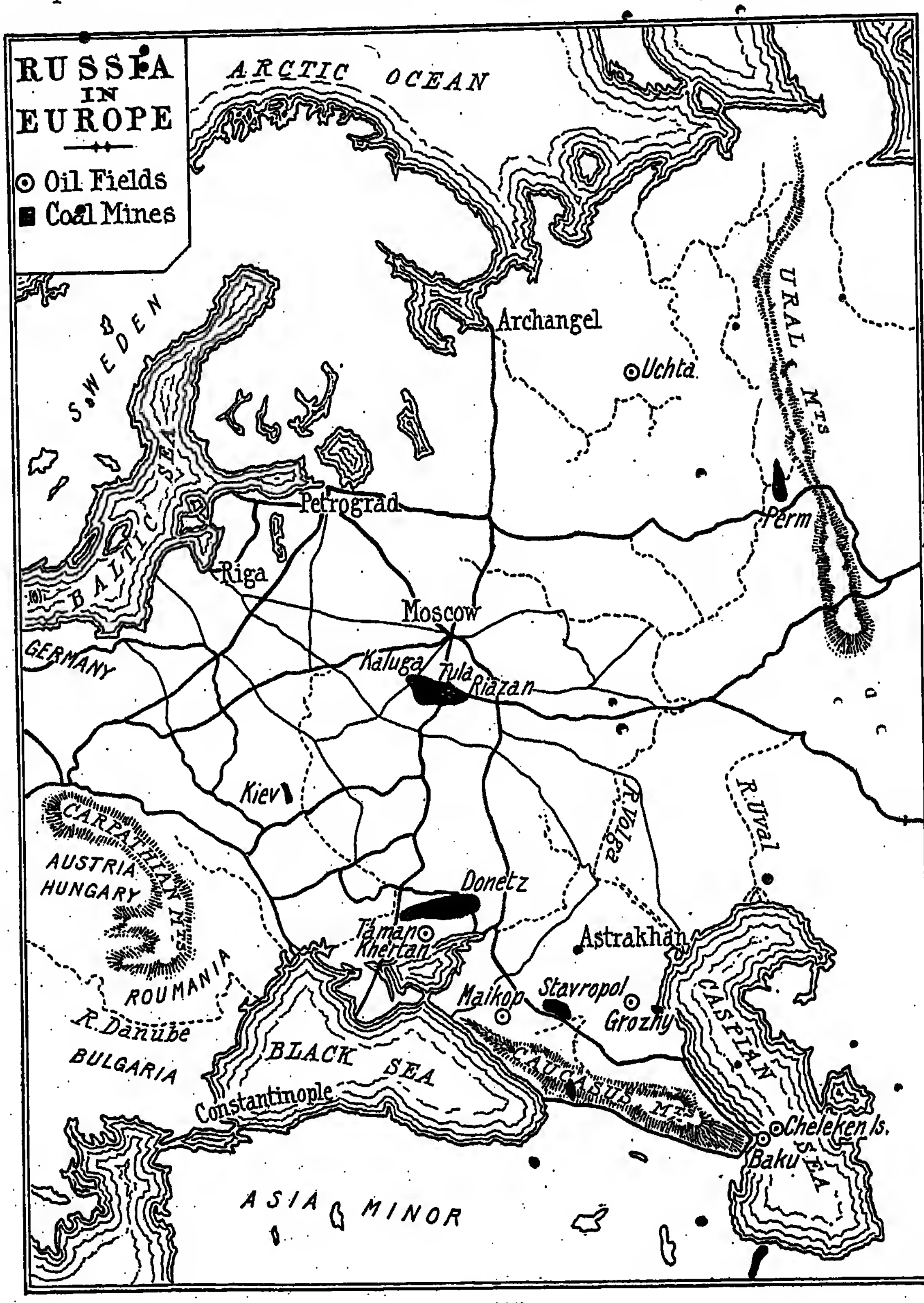

Fig. 3.

in the Crimea from Sebastopol to Yalta, and a series of mineral railways in the Caucasus, viz. Armavir–Tuapse; Saramis–Karaklis; Quiriky–Michailovo; and Vladikavkaz–Tiflis. Up to the present, however, nothing has been done to further these schemes.

This inactivity is temporary and is entirely governed by considerations of an economic nature. It seems, however, that the eventual electrification of the railways will proceed along lines quite different from those adopted in the main scheme, which has been briefly outlined in the preceding paragraphs. There, the immediate object was the long main-line electrification. The present schemes put forward are concerned, not with the main-line electrification, but with the electrification of railways according to a district basis. As soon as the erection of the power stations has been started in certain districts, it is suggested that the electrification of the railways in these districts will achieve two objects at the same time, viz. provide the stations with a load, and enable the railways to obtain sufficient power for their present needs.

It is suggested that the electrification of railways should take place in three districts, viz. Moscow, Petrograd and Donec, the railways near Moscow being in a particularly favourable position because of the close proximity of their power stations. Four very powerful stations, viz. the Electro Transmission, the Moscow, the Kashira and the Shatura stations could supply energy for these railways. These four stations will towards 1930 have a total capacity of not less than about 200 000 kW, and the following network of railways could be supplied from them:—

Moscow–Tula	Moscow–Riazan
Moscow–Kashira	Moscow–Vlagimir
Moscow–Shatura	Moscow–Pushkino

and the Moscow Circle Railway (see Fig. 4).

The total mileage of the last-named is about 700 miles, taking into account the 140 miles of suburban railways. It is suggested that towards 1930 these railways could take 50 000 kW, but with further development they would require up to 200 000 kW, by which time it is hoped that the power capacity of the stations will be increased correspondingly. The erection of several other stations near Moscow will allow of an expansion of the electrified area. The financial strain of such a scheme on the State is much lighter than would be that of long-line electrification, since in district electrification the whole work can be spread over a long period and need not necessarily be completed at once. If 80 to 100 miles of lines be electrified yearly, the whole electrification of the Moscow district would be completed by 1933 and would involve an expenditure

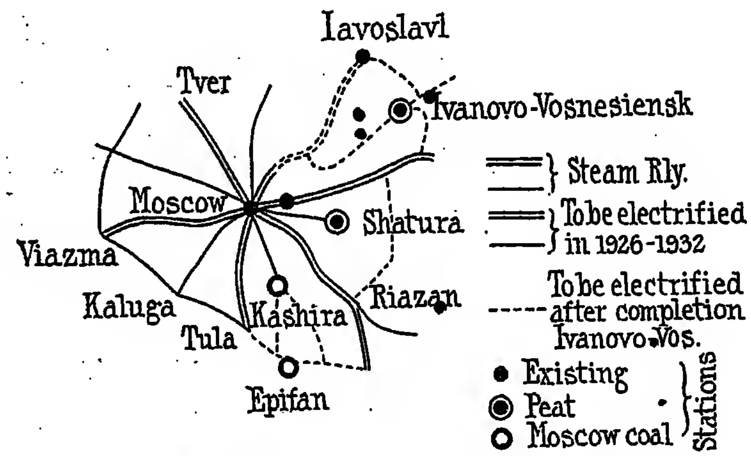

FIG. 4.—Railway electrification of Moscow.

of about £4 000 000; in other words, a yearly expenditure of, say, half a million sterling.

CONCLUSION.

An attempt has been made to give an outline of Russian economics with special reference to the question of electrification, and of the present state and existing tendencies of electrical developments. There seems to be an enormous amount of work to be done in Russia, and no doubt this will be accomplished sooner or later.

The Russian industry is not at present capable of satisfying all the demands of the Russian market. However rapidly the industry grows, for a considerable time to come a large proportion of the electrical requirements of Russia will have to be imported into the country. Apart from that, a tremendous amount of purely technical work will have to be done inside Russia, and this will require the services of a considerable number of technically trained engineers, far in excess of those to be found in that country.

The British electrical industry has definitely become an exporting one, and its future success will greatly depend upon the volume of such work. The interest in foreign markets should, therefore, be a natural one to those concerned with this industry.

The possibilities to be found in Russia should be of overwhelming interest to British electrical engineers, and if such interest has been stimulated by this paper the authors will feel that it has served its purpose.

DIRECTIONS FOR THE STUDY OF ELECTRICAL INSULATING VARNISHES, PAINTS AND ENAMEL PAINTS.*

[REPORT (REF. A/S9) RECEIVED FROM THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

CONTENTS.

PREFACE.

The difficulty of carrying out suitable tests on varnishes to determine whether they are satisfactory for use in electrical machinery has been experienced by those who have attempted such investigations. These Directions have been developed with a view to the study of the more important properties of varnishes intended for electrical insulating purposes.

In view of the need for this Publication it has been decided to issue it in its present form, although the most satisfactory methods for carrying out certain of the tests have not been settled.

It is hoped that all those who have occasion to test electrical insulating varnishes will adopt the methods suggested herein, so that results obtained by different investigators may be strictly comparable, and that the essential characteristics of this class of varnishes may be determined.

The Director of the E.R.A. will welcome comments and criticism from those who use this Publication.

I. INTRODUCTION.

The tests described herein are intended for varnishes, etc., that are applied by brushing, dipping or spraying, and are primarily employed for the purpose of providing electrical insulation.

In the clauses describing the methods of test the term "varnish" includes paint, enamel, binder and impregnating material.

II. DEFINITIONS.

1. INSULATING VARNISH.

The term "insulating varnish" denotes a liquid that yields on drying a protective insulating film.

(a) *Spirit varnish.*

The term "spirit varnish" denotes a liquid made with a base of resin or gum dissolved in a spirit, drying only by the evaporation of the solvent relatively quickly at atmospheric temperature, and yielding a protective insulating film.

NOTE.—A lacquer is a thin, quick-drying protective varnish, and is generally applied to a metal surface.

(b) *Oil varnish.*

The term "oil varnish" denotes a drying oil, generally with resin or gum, that yields on drying a protective insulating film.

2. PAINT.

The term "paint" denotes a mixture of pigment with a liquid vehicle.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

(*a*) *Oil paint.*

The term "oil paint" denotes a mixture of pigment with a drying oil.

(*b*) *Enamel paint or enamel.*

The term "enamel paint" or "enamel" denotes a mixture of pigment with a varnish.

NOTE.—An enamel generally contains less pigment than an oil paint.

3. PIGMENT.

The term "pigment" denotes the fine solid particles used in the preparation of paint, and substantially insoluble in the vehicle.

4. BITUMINOUS ENAMEL.

The term "bituminous enamel"—stoving or air-drying—denotes a liquid made with a bituminous base that yields on drying a smooth protective film.

This class of enamel contains no pigment.

NOTE.—The term "japan" has been discarded in view of the confusion existing in the use of this term.

5. BINDER OR BOND.

The term "binder" or "bond" denotes any substance employed as an adhesive between the several layers of built-up laminated insulating material.

6. IMPREGNATING MATERIAL.

The term "impregnating material" denotes any substance employed to impregnate the interstices of a porous mass of winding or insulation.

7. BASE.

The term "base" denotes the film-producing or impregnating substance from which the materials defined above are made. The base remains behind or undergoes some physical and/or chemical change after the volatile constituent, if any, has disappeared.

8. VOLATILE THINNER.

The term "volatile thinner" denotes the liquid employed to reduce the viscosity of the materials defined above.

III. TESTS.

9. SPECIFIC GRAVITY.

The specific gravity at 20° C., referred to water at the same temperature, shall be determined either by a standard pyknometer specific gravity bottle, specific gravity balance, or hydrometer. All usual precautions as to standardization of vessels shall be adopted by checking against distilled water. The temperature of the varnish shall be between 15° C. and 25° C. when tested, and the specific gravity shall be corrected to 20° C.

10. VISCOSITY.

The viscosity shall be determined at a temperature of 20° C. in accordance with the British Standard Method for the determination of Viscosity in Absolute Units, British Standard Specification No. 188.

11. FLASH POINT.

The closed flash point shall be determined in the Abel or the Pensky-Martens apparatus.

12. FIRE POINT.

The fire point shall be determined as specified in the American Society for Testing Materials (A.S.T.M. Method D92–21T, Tentative Standards 1922).

13. DRYING.

(*a*) *Drying of surface film.*

The test shall be carried out on either Japanese Gampi tissue paper approximately 1 mil thick, or on sheet copper or brass about 5 mils thick. The dimensions of the specimen shall be approximately 8 inches long and 6 inches wide.

(i) *Preparation of specimens.*

The density of the varnish to be employed for the drying test shall be so adjusted by trial with the thinner recommended by the varnish manufacturer that the thickness of the varnish film on each side of the paper or metal sheet shall be not less than 3 mils, and not more than 3·5 mils, in the vicinity of the centre of the specimen.

To obtain the required thickness of film the varnish shall be diluted with the solvent recommended by the varnish manufacturer, and the paper or metal shall be varnished as follows:—

To determine the correct density of the varnish, strips of paper or metal shall be dipped in samples of diluted varnish containing amounts of thinner ranging from 5 per cent to 50 per cent (by volume). After draining for 30 minutes at room temperature, approximately 20° C., the specimen shall be dried as specified in (ii) below. Each specimen shall then be dipped again in varnish of the same density as before, drained for 30 minutes at room temperature, and dried as specified in (ii) below. During the draining, care shall be taken that the specimens remain stationary. When being dipped, drained and dried the second time the specimens shall be suspended in the opposite direction to that employed for the first film. The depth of the varnish in which the specimen is dipped shall be about ¾ inch, and the specimen shall be immersed completely for approximately 1 minute, care being taken to remove all froth. The specimen shall be drawn through the varnish at the same rate as the excess of varnish slips from the surface of the specimen.

NOTE.—If none of the specimens is of the specified thickness, the required density of the varnish may be obtained by interpolation.

(ii) *Method of drying.*

Six specimens coated with air-drying varnish shall be dried in free air at a temperature from 20° C. to 25° C.

Six specimens shall be dipped in baking varnish as specified in (i) above and allowed to drain for 30 minutes at room temperature, approximately 20° C., and then dried in an oven heated externally at a temperature from 95° C. to 100° C., unless the varnish manufacturer

recommends a higher temperature. The air content of the oven shall be changed completely not less than three times per hour. After the first coat has been dried the specimens shall be removed from the oven and allowed to cool to air temperature, approximately 20° C.; they shall then be dipped a second time and drained and dried as before. When being dipped, drained and dried the second time the specimens shall be suspended in the opposite direction to that employed for the first film.

The first specimen shall be tested as specified in (iii) below, 30 minutes before the expiration of the time stated by the varnish manufacturer, and thereafter further specimens shall be tested similarly at intervals of 10 minutes.

(iii) *Time of drying.*

The varnish shall be considered dry when a circular piece of No. 4 Whatman filter paper 1⅝ inch diameter does not adhere to the varnish when it is pressed on the surface of the varnish for one minute by a cylindrical weight of one pound, one inch in diameter. The filter paper shall be applied in the vicinity of the centre of the specimen. The test shall be carried out at a temperature from 15° C. to 25° C.

(*b*) *Drying throughout a mass of winding.*

The test to determine the drying property of a varnish throughout a mass of winding shall be carried out on coils of double cotton covered copper wire. The coil employed for the test shall be of circular section, approximately 2 inches internal diameter and 2 inches long. The coil shall be wound with wire 0·036 inch diameter, double cotton covered, and the depth of the winding shall be approximately ½ inch.

The time required for the varnish to dry satisfactorily shall be determined as follows:—

Several specimen coils shall be provided which shall be thoroughly dried in a hot vacuum oven and immediately immersed for ten minutes in a bath of the varnish at the density recommended by the manufacturer, or other trial density. After draining, the coils shall be baked at different temperatures and for different periods of time, the varnish maker's recommendations being taken as an initial guide. When cold, the coils shall be sawn through and the several layers and turns separated. The baking conditions necessary to obtain effective adhesion between the cotton covered wires throughout the mass of the winding shall be recorded.

14. Electric Strength.

The electric strength test shall be carried out on either varnished Japanese Gampi tissue paper or varnished sheet copper or brass. The paper employed for the test shall be approximately 1 mil thick and the metal sheet about 5 mils thick.

The paper or metal sheet shall be varnished and dried as specified in Clause 13 (*a*).

Sufficient specimens shall be varnished to enable ten tests to be carried out at each of the temperatures given below.

The electric strength tests shall be carried out at a temperature from 20° C. to 25° C. and at a temperature from 90° C. to 95° C. within 24 hours of the completion of the drying of the second coat of varnish.

The electrodes shall make contact with the varnish in the vicinity of the centre of the specimen.

The potential difference shall be raised from zero, in steps of not more than 250 volts, at the rate of 30 kilovolts per minute until breakdown occurs.

In other respects the electric strength test shall be carried out in accordance with Technical Publication Ref. L/S2, Tentative Directions for the Determination of the Electric Strength of Solid Dielectrics, except where otherwise specified in this Clause.

In each test the thickness of the varnish film shall be determined from the mean of three measurements of thickness taken as close to the point of puncture as practicable.

The puncture voltage, the total thickness of the specimen and the net thickness of the varnish film shall be stated for each of the ten tests at each temperature, and the maximum, minimum and mean values of the volts per mil of the varnish film shall be given.

15. Waterproof Tests.

The waterproof properties of the varnish shall be determined by the following tests:—

(*a*) *Resistance to moisture.*

The ability of the varnish to resist moisture shall be determined by carrying out the electric strength test specified in Clause 14 after the specimen has been subjected to an approximately saturated atmosphere (relative humidity not less than 95 per cent) for 3 days. The electric strength test shall be carried out whilst the specimen is in the moist atmosphere at a temperature from 20° C. to 25° C.

(*b*) *Water permeability test.*

This test shall be carried out as follows:—

A clean smooth copper or brass sheet approximately 10 inches square and 5 mils thick shall be coated on one side only either by spraying or pouring the varnish over the sheet. The density and viscosity of the varnish shall be adjusted in accordance with conditions specified by the varnish maker.

The thickness of the film shall be measured at 20 points equally spaced over the area of the sheet. The thickness at any point shall not vary from the mean value by more than 1 mil, and the mean value shall be taken as the thickness of the varnish film. In each quarter of the sheet a ring of wax approximately 2½ inches internal diameter and ⅛ inch deep shall be made on the varnish. The four rings shall be filled with distilled water and left for a period of 24 hours. The water shall then be removed as far as possible with a pipette, the remainder being absorbed by blotting paper or similar material. The sheet shall be left for 5 minutes to dry off at a temperature from 20° C. to 25° C. The electric strength of the varnish shall then be determined at two positions in each quarter of the sheet, one inside the ring of wax and the other outside, but as close to the ring as possible, care being taken that the varnish surface on which the electrode is placed is entirely free from wax.

The upper electrode shall be a solid cylinder of brass $1\frac{1}{2}$ inches long and $1\frac{1}{2}$ inches diameter. The electric strength test shall be carried out at a temperature from 20° C. to 25° C. The electric strength test shall be carried out in accordance with Technical Publication Ref. L/S2, Tentative Directions for the Determination of the Electric Strength of Solid Dielectrics, except where otherwise specified in this Clause.

Comparison shall be made between the mean values of the four puncture voltages inside and outside the rings respectively, and the percentage decrease computed on the mean outside value shall be stated.

16. Ageing.

The ageing test shall be carried out on Japanese Gampi tissue paper on specimens varnished and dried as specified in Clause 13 (*a*). After removing not less than $\frac{1}{2}$ inch from one edge, six strips each $\frac{3}{4}$ inch wide shall be cut from that edge.

The strips shall be placed in a uniformly heated oven at a temperature from 100° C. to 105° C. A strip shall be removed at the end of 50, 100, 200, 300, 400 and 500 hours respectively and shall be tested at room temperature, approximately 20° C., as specified below, between half-an-hour and one hour after removal from the oven.

Each strip shall be bent double under a weight of one pound, the dimensions of the base of which shall be 1 inch square, and the effect on the varnish at the bend shall be noted. The number of hours that the varnish has been heated when it first cracks in the bending test shall be stated.

17. Effects of Acids and Alkalies.

The ability of the varnish to withstand acids and alkalies shall be determined at a temperature between 15° C. and 25° C. by the following tests:—

(*a*) A number of copper rods each approximately $\frac{1}{4}$ inch diameter and about 6 inches long, one end being rounded and the other having a suitable terminal, shall be brightly burnished, washed clean with dilute alcohol and then dried in warm air; whilst still warm they shall be dipped carefully without agitation into the varnish and dried as specified in Clause 13 (*a*).

When dry the rounded end of each rod shall be coated with paraffin wax to a distance of approximately 2 cm.

A zinc rod, such as is used in Leclanché batteries, shall be well amalgamated with mercury, and immersed centrally into a vessel containing an aqueous solution of sulphuric acid, specific gravity 1·182 at 15°/4° C. (25 per cent by weight of H_2SO_4); the lower end of the zinc rod shall dip into a small cup containing mercury (to maintain the amalgamation), whilst the copper rods shall be spaced round the zinc rod at a radius of 5 cm. The zinc rod shall be connected to one terminal of a millivoltmeter, while each of the copper rods shall be successively connected up and the potential difference noted.

The millivoltmeter used shall have a range of 1 500 millivolts and a resistance of 60 ohms (plus or minus 10 per cent) at 20° C. If an instrument of lower resistance be used, then a resistance shall be inserted in series to make up the difference, and the readings multiplied by a correction factor to give the millivolts across the instrument and external resistance. If an instrument of higher resistance be used it shall be shunted with a suitable resistance.

It is important that no difference of potential is indicated at the commencement, and should any occur the rod shall be rejected and a fresh one put in its place. The rods shall be tested every hour for the first few hours to study the effect, and then at intervals of 6, 12 or 24 hours.

(*b*) The varnish shall be tested as described in (*a*) except that the solution in which the rods are immersed shall be a 10 per cent solution of caustic soda (NaOH) prepared with distilled water (specific gravity equals 1·13).

(*c*) A standard Soxhlet thimble, approximately 2 cm by 8 cm (as made by Whatman, or similar thimble) shall be coated with two coats of the varnish under test either by dipping or brushing and shall then be dried in accordance with Clause 13 (*a*). It shall be filled to within $\frac{1}{2}$ inch of the top of the varnish film with a 10 per cent solution of caustic soda (NaOH). It shall be then supported by suitable means in a freshly prepared solution of phenol phthalein in distilled water, dipping to the same level as the alkali inside. The time expressed in minutes taken for the solution in the immediate vicinity of the thimble to turn pink in colour due to the alkali shall be noted.

(*d*) The following tests shall be carried out on sheet copper specimens about 5 mils thick and $\frac{3}{4}$ inch wide. The specimens shall be varnished and dried as specified in Clause 13 (*a*).

The specimens shall be immersed in the reagents given below at a temperature from 15° C. to 25° C. for approximately 16 hours, and suspended in an air oven at atmospheric temperature for the remainder of the 24 hours. This procedure shall be carried out for six days consecutively, and the effect of the reagents on the varnish shall be stated.

Reagents :

- Sulphuric acid, specific gravity 1·4.
- Hydrochloric acid, specific gravity 1·1.
- Nitric acid, 5 per cent solution.
- Picric acid, 2·5 per cent aqueous solution.
- Ammonia (0·88), 10 per cent solution.
- Mixture of ammonium chloride and sulphate, a saturated aqueous solution.
- Caustic soda, specific gravity 1·13 (10 per cent NaOH).

18. Effect of Oil.

The ability of the varnish to withstand hot oil shall be determined by the following tests:—

(*a*) Specimens of Rope paper shall be varnished and dried as specified in Clause 13 (*a*). The paper shall be in accordance with the Rope paper defined in Technical Publication Ref. A/S5, Directions for the Study of Electrical Insulating Papers (Unvarnished) for Purposes other than the Manufacture of Cables.*

The effect of oil on the varnish shall be determined

* *Journal I.E.E.*, 1923, vol. 61, p. 982.

by immersing a number of varnished specimens in the oils specified below at a temperature from 115° C. to 120° C. The specimens shall be examined at intervals, and the period required for the varnish to be affected by the oils shall be determined. The effect on the varnish shall be stated, for example, by the formation of sludge on the varnish.

(i) Transformer oil complying with B.S.S. No. 148—1923 for light grade oil.

(ii) Lubricating oil, which shall consist of a mineral oil with 20 per cent of blown rape oil, and shall comply with the following specification:—

Specific gravity at 60° F. (15·6° C.)	0·92 (approximately).
Closed flash point	Not less than 370° F. (188° C.).
Viscosity (time of outflow of 50 cm^3 in Redwood viscometer)	75 seconds at 200° F. (93° C.); 38 seconds at 300° F. (149 °C.).
Acidity, calculated as oleic acid	Not more than 1 per cent.
Loss in 2 hours at 212° F. (100° C.) (determined as described below)	Not more than 0·3 per cent.

The oil shall be free from mineral acid.

The loss at 212° F. (100° C.) shall be determined by heating 9 grammes of oil in a flat-bottomed porcelain dish approximately 2½ inches diameter and ¾ inch deep.

(*b*) The test for the effect of oil shall be carried out on a coil of cotton covered copper wire. The coil employed for the test shall be of circular section approximately two inches internal diameter and two inches long. The coil shall be wound with wire 0·036 inch diameter double cotton covered, and the depth of the winding shall be approximately ½ inch. Before the application of varnish to the coil, it shall be dried for six hours in an oven at a temperature from 95° C. to 100° C. The coil shall then, whilst still hot, be dipped in the varnish under test, and allowed to remain immersed for a minimum period of 5 to 10 minutes or until such time as all bubbling ceases. It shall then be removed from the varnish, allowed to drain, and placed in a drying oven for 18 hours at a temperature from 95° C. to 100° C., unless the varnish manufacturer recommends a higher temperature. The coil shall then be again dipped for a further period of about five minutes, and the drying operation carried out as before.

The effect of oil on the varnish shall be determined by immersing coils in the oils specified in (*a*). The test shall be carried out as specified in (*a*), and the effect on the varnish shall be stated, for example, by the formation of sludge on the varnish and by the loss of adhesion between the turns of the coil.

19. Effect of Varnish upon Copper.

Note.—Electrical insulating varnishes, other than those of the synthetic resin type, usually contain organic acids.

The ordinary tests for acidity do not furnish sufficient information to determine whether a varnish is likely to have an injurious effect on copper.

This subject is under consideration with a view to the development of a suitable test.

20. Effect of Corona Discharge.

Note.—A test to determine the effect of corona discharge on varnish is under consideration.

21. Effect of Producer Gas.

Note.—A test to determine the effect of producer and similar gases on varnish is under consideration.

22. Permanence of Coloured Enamels (used for Marking and not for Insulating Purposes).

Note.—An investigation is in hand with a view to the development of suitable tests.

INDUCTIVE INTERFERENCE WITH COMMUNICATION CIRCUITS.*

By Dr. ALEXANDER RUSSELL, F.R.S., President.

(*Paper received* 15*th August*, 1924.)

SUMMARY.

The paper discusses interference between power circuits and telegraph and telephone circuits. A distinction is made between "radiation" and "induction." The former cause produces both electric and magnetic effects and is used in radio-telegraphy. The conductivity of the earth, which is not a homogeneous body, should be taken into account. Experiment, however, shows that in radio work we can get approximate solutions by assuming that the earth is a non-conductor and that its inductivity is unity. Making this assumption, it is shown that the intensity of the "radiation" field in simple cases falls off inversely as the distance and inversely as the wave-length. On this assumption also the intensity of the induction field, whether electrostatic or electromagnetic, obeys this law in a few cases. It is pointed out that a balanced three-phase system produces both electric and magnetic rotary fields in its neighbourhood, the amplitudes of which fall off according to the inverse square of the distance. A three-phase four-wire system, however, may produce serious interference with telephone systems even when the phases are balanced. In an appendix an easy method of finding the numerical value of the mutual capacity coefficient between two spheres is given.

When the Secretary of the London Students' Section asked me to give an address to the Section I felt that it was my duty to do so; but I also felt that I should be free to choose the subject for the address. It is expected on these occasions that the President should give some useful advice to those on the threshold of the profession. Last year on a very similar occasion it was put very bluntly to me. The Students wanted to know how best they could utilize in the industrial world the knowledge they had acquired in college. Paraphrased slightly, I took this to mean: What is the easiest way of getting a well-paid job? Although I ventured to say something in this connection last year with the object of interesting my audience, I thought that on this occasion I should say something with the object of interesting myself. Naturally I thought that some mathematical subject would be suitable, although from the eloquent silence of the secretary of the Students' Section I inferred that in his opinion it would not be a happy choice so far as my audience was concerned. I therefore sought for some mathematical subject which would have an immediate practical bearing on industry. I only chose the subject, however, last night after listening to a valuable paper on "Power Circuit Interference with Telegraphs and Telephones" which was read † by Mr. S. C. Bartholomew before the Institution. It seemed to me that a talk on the inductive interference of power circuits with communication circuits would be useful at the present time. There are many problems still to be solved which are of interest to the mathematician and the experimentalist. In what follows I shall attempt to give a survey of the problem from the mathematical point of view in the hope that some Students will amend some of the assumptions which it is necessary to make, and extend or perfect many of the theorems given. In this connection many useful formulæ and some valuable data will be found in Eccles's handbook on "Wireless Telegraphy and Telephony."

So many young engineers are now radio experts that they naturally think that radiation from power lines may be one of the causes of interference. Radiation has been defined as the moving disturbance in the ether, the energy connected with which does not return to the radiator. It is this disturbance which is considered in modern radio-telegraphy.

From the engineering point of view we may discuss radiation as follows: Consider a small electrified body O in infinite space and let it have an electric charge q. The potential v at a point P at a distance x from O is given by

$$v = \frac{q}{x} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Now if q changes, v changes. But it is against all physical principles to assume that the change takes place instantaneously. We shall adopt Maxwell's theory, and suppose that the electric effects are propagated with the velocity u of light. We can suppose, therefore, that there is a time-lag x/u between the varying charge q and the varying potential at the point P. If q follow the harmonic law, we can write $q = Q \sin \omega t$, where $\omega = 2\pi/T$, T is the periodic time and t the number of seconds since the epoch of reckoning. We shall make the supposition that the potential at P has the retarded value given by

$$v = \frac{Q}{x} \sin \omega\left(t - \frac{x}{u}\right) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Mathematical reasons can be given for this supposition, but as it is the simplest that could be made we shall adopt it.

By definition, the electric force F at P in the direction OP is given by

$$F = -\frac{\partial v}{\partial x}$$
$$= \frac{Q\omega}{ux} \cos \omega\left(t - \frac{x}{u}\right) + \frac{Q}{x^2} \sin \omega\left(t - \frac{x}{u}\right)$$

* Part of this paper was given in an Address to the London Students' Section on the 11th April, 1924.

† *Journal I.E.E.*, 1924, vol. 62, p. 817.

If λ be the wave-length of the disturbance in the ether, $\lambda = uT$, $\omega = 2\pi u/\lambda$ and, therefore,

$$F = \frac{2\pi Q}{\lambda x} \cos \omega\left(t - \frac{x}{u}\right) + \frac{Q}{x^2} \sin \omega\left(t - \frac{x}{u}\right) \quad . \quad (3)$$

We see, therefore, that one effect of the finite velocity of propagation is to increase the value of F by a term the amplitude of which is $2\pi Q/(\lambda x)$.

Formula (3) shows that the electric force at P, which is in the direction OP, consists of two components. The first component has an amplitude $2\pi Q/(\lambda x)$. This is called the "radiation" component. The second component has an amplitude Q/x^2 and is called the component due to electric induction. When x is small compared with λ the induction component is the more important. When $x = \lambda$, the first component is more than six times greater than the second, and when x is large compared with λ, the "radiation" (and not the "induction") has to be considered. It is customary to consider only the radiation in radio theory, and when discussing interference troubles it is usual to consider only the inductive effects. It is well to bear in mind, however, that both effects are always in action when the electrification is varying.

In what precedes we have only discussed the electric field. But if we had discussed the magnetic field of a small current element of length l and carrying a current I we should have found that the magnetic field H at a point on the equatorial plane at a distance x from the element was given by *

$$H = \frac{2\pi lI}{\lambda x} \cos \omega\left(t - \frac{x}{u}\right) + \frac{lI}{x^2} \sin \omega\left(t - \frac{x}{u}\right) \quad . \quad (4)$$

We see as before that the first term is due to radiation and the second to induction. From Maxwell's theory it follows that in the case of radiation the electric field is always accompanied by a magnetic field, and vice versa. These fields can be regarded as aspects of the same phenomenon and are in a constant ratio to one another. The effects produced in the receiving aerial can be computed by considering either the electric or the magnetic component. Radiation, therefore, cannot be described as exclusively an electric or a magnetic phenomenon. Neglecting absorption and assuming a homogeneous dielectric and a non-conducting earth we see that the electric and magnetic forces fall off inversely as the distance and inversely as the wave-length. This has been roughly verified in certain cases by several experimenters.

The interference produced by low-frequency power circuits in connection with telegraphy and telephony is mainly due to induction. In this case we have to distinguish between electric and magnetic induction, and both have to be taken into account. It seems to me that power engineers lay too much stress on magnetic induction, and telephone engineers on electric induction. In practice both effects take place simultaneously. To calculate them it would be necessary to know both the mutual electrostatic and the mutual electromagnetic coefficients between various kinds of circuits. Several of the latter coefficients are given in textbooks and are fairly easy to compute, but with the exception of the case of two spheres very little has been done towards calculating the mutual electrostatic coefficients of circuits. Personally I have tried to solve several problems of this nature, but with only partial success. It is only possible in this paper to give an introduction to a wide field which wants mathematical and experimental exploration, and to touch in a sketchy way on some of the problems that have to be considered. I hope that some Students will be able to suggest better methods of attacking the problems.

Before proceeding further we must face the question of whether we are going to consider the earth as a conductor or as an insulator for electric currents. If we adopt the former assumption we shall be forced to make the further assumptions that it is a homogeneous conductor and that its conductivity remains constant. As a matter of fact we know that it is a conductor. In certain cases its conductivity in the neighbourhood of buried wires has been measured. We know also that when an alternating potential difference of constant effective value is maintained between a long insulated horizontal wire and the earth, the charging current varies from day to day and in certain cases from hour to hour. It obviously depends on the amount of moisture on the surface of the earth. The earth therefore must be considered as a heterogeneous conductor. This enormously increases the difficulty of getting accurate solutions.

To enable us to get approximate solutions we must either consider the earth to be an insulator the inductivity of which equals unity or that its surface may be considered to be a perfect conductor. If we suppose the small conductor O considered above to be at a distance H above a perfectly conducting plane, and if OP be parallel to the plane and very great compared with H, then for the amplitude of the electric force F of radiation we have, by the method of electric images,

$$F = \frac{2\pi Q}{\lambda x} - \frac{2\pi Q}{\lambda\sqrt{(x^2 + 4H^2)}} = \frac{4\pi Q H^2}{\lambda x^3} \text{ (approx.)}$$

The radiation effect would, therefore, fall off with extreme rapidity, obeying the law of the inverse cube of the distance. So far as radio communication is concerned, the assumption that the earth is an insulator leads to the best results. We shall therefore adopt it in what follows. When we have obtained formulæ assuming the earth to be an insulator, the corresponding formulæ taking the earth as a perfect conductor can be written down at once by the method of images.

We shall consider the electric and the magnetic forces separately. In practice they occur simultaneously, but if we attempted to give a complete solution so many variables occur in it that the formula would be very complicated and therefore of little practical help. We shall first consider electrostatic induction.

Electrostatic Induction.

Let us take the case of two insulated conductors A and B at a considerable distance x apart. Let v_1, v_2

* J. H. Dellinger: Bureau of Standards, Scientific Paper No. 354 (1919).

and q_1, q_2 be the potentials of and the charges on A and B respectively. We see that

$$v_1 = \frac{q_1}{K_1} + \frac{q_2}{x}; \text{ and } v_2 = \frac{q_2}{K_2} + \frac{q_1}{x} \quad . \quad . \quad (5)$$

approximately, where K_1 is the ratio q_1/v_1 when q_2 is zero. K_1 and K_2 are practically, therefore, the capacities of the conductors A and B respectively to earth. If the conductors A and B were spheres, ellipsoids, rings, discs or thin rods the ordinary formulæ show that K_1 and K_2 are very minute compared with x. Solving (5) for q_1 and q_2 we get

$$q_1 = \frac{x^2K_1}{x^2 - K_1K_2} v_1 - \frac{K_1K_2x}{x^2 - K_1K_2} v_2$$

$$= K_1v_1 - \frac{K_1K_2}{x} v_2 \text{ (very approx.)} \quad . \quad . \quad (6)$$

and $$q_2 = K_2v_2 - \frac{K_1K_2}{x} v_1 \text{ (very approx.)} \quad . \quad . \quad (7)$$

when K_1 and K_2 are very small compared with x.

If v_1 were given by $E \sin \omega t$ and the conductor B were earthed ($v_2 = 0$), the current i_2 in the earthing wire of B would be given by

$$i_2 = -\frac{\partial q_2}{\partial t} = \frac{K_1K_2}{x} \omega E \cos \omega t$$

$$= \frac{2\pi K_1K_2u}{x\lambda} E \cos \omega t \quad . \quad . \quad (8)$$

where u is the velocity of light and λ is the wave-length of the radiation ($\omega = 2\pi u/\lambda$).

Hence the current induced in the earthing wire of B when the potential of A varies according to the harmonic law, is proportional to K_1, to K_2 and to the amplitude of the potential. It is also inversely proportional to x and λ.

Let us now consider a very long and thin conducting prolate spheroid. The ellipsoid is considered so long and so thin that it is practically a wire, the foci S and H of the elliptic sections being at its ends. The electrification of a conducting ellipsoid was a problem much studied by mathematicians 50 years ago as exact solutions were obtainable, and many curious properties came to light. For example, all ellipsoids confocal to the given ellipsoid were found to be equipotential surfaces of the given ellipsoid. We suppose that the prolate spheroid is so thin that it practically represents the line SH. It is known that if a wire conductor of this shape be electrified the charge on it per unit length of SH will be the same. It will therefore act like a wire having an electric charge uniformly distributed along it.

If q be the total charge on the prolate spheroid it can be shown that the potential v at any point P is given exactly by

$$v = \frac{2q}{\text{SH}} \text{ arc tanh } \frac{\text{SH}}{\text{SP} + \text{PH}} \quad . \quad . \quad . \quad (9)^*$$

which is a remarkably simple expression.

* Those not familiar with inverse hyperbolic trigonometry may convert the inverse tangent into Napierian logarithms or into algebra by the formulæ

$$\text{arc tanh } x = \tfrac{1}{2} \log_e (1 + x) - \tfrac{1}{2} \log_e (1 - x) = x + \frac{x^3}{3} + \frac{x^5}{5} + \ldots$$

Expression (9) proves at once that the equipotential surfaces round SH are prolate spheroids the foci of which are S and H.

When CP is very great, where C is the middle of SH, we can write SP = PH = CP and $v = q/\text{CP}$. The problem thus reduces to the preceding case.

If SH $= 2a$, CP $= x$ and $\angle$SCP is a right angle so that P lies on the equatorial plane, we have

$$v = \frac{q}{a} \text{ arc tanh } \frac{a}{\sqrt{(a^2 + x^2)}} \quad . \quad . \quad . \quad (10)$$

The electric force F at P in the direction CP is given by

$$F = -\frac{\partial v}{\partial x} = \frac{q}{x\sqrt{(x^2 + a^2)}} = \frac{q}{\text{CP . SP}} \quad . \quad (11)$$

When P lies on HS produced,

$$v = \frac{q}{a} \text{ arc tanh } \frac{a}{x}$$

and thus $$F = \frac{q}{\text{CP}^2 - \text{CS}^2} \quad . \quad . \quad . \quad . \quad . \quad (12)$$

Formulæ (11) and (12) enable us to compute easily the electric force at points on the equatorial plane and along the polar axis.

If the ends of a thin wire in the equatorial plane be at points where the potentials due to SH are different, a current will obviously be induced in the thin wire by electric induction. Similarly a wire placed along the polar axis will have a current induced in it.

When the wire SH is long and the distance of a point P on the equatorial plane from C is not great, CP is practically equal to SP and so

$$F = \frac{q}{a \times (\text{CP})} \text{ (approx.)}$$

In this case also if P be on the polar axis

$$F = \frac{q}{(\text{CP} + \text{CS})(\text{CP} - \text{CS})}$$

$$= \frac{q}{2a \times (\text{SP})} \text{ (approx.)}$$

Thus the electric intensity is greater at a point in the equatorial plane than at a point on the polar axis at the same distance from the wire.

Let us now consider two infinitely long parallel wires at a distance x apart. Let the radius of the cross-section of each of them be a and let q_1, q_2 and v_1, v_2 be the charges per unit length and the potentials of the wires respectively. In this case it is known that

$$q_2 = k_{22}\, v_2 + k_{12} v_1$$

where k_{22} and k_{12} are constants called Maxwell's capacity coefficients. The computation of the values of these constants is difficult, but when the wires are far apart it can be shown that

$$k_{22} = -k_{12} = \frac{1}{4 \log (x/a)} \text{ (approx.)}$$

* A. Russell: *Proceedings of the Physical Society*, 1919, vol. 31, p. 123.

Thus if v_2 be zero and $v_1 = E \sin \omega t$, we find that the current i_2 in the earthing wire is given by

$$i_2 = -\frac{\partial q_2}{\partial t} = \frac{1}{4 \log (x/a)} \omega E \cos \omega t$$
$$= \frac{\pi u E}{2\lambda \log (x/a)} \cos \omega t \quad . \quad . \quad . \quad . \quad (13)$$

As x is great compared with a, i_2 varies very slowly with x.

Electromagnetic Induction.

As a rule, students pay much more attention to electromagnetic induction than to electric induction. Problems in connection with magnetic induction linking circuits together are therefore much more familiar to them.

Let i_1 be the current in the disturbing circuit and let L_{12} be the mutual induction between it and the disturbed circuit. Then we know that the disturbing E.M.F. induced in the latter is $L_{12}(\partial i_1/\partial t)$. This E.M.F. depends on the factor L_{12} and on how the disturbing current varies with the time.

If we have a small current element of length l_1 carrying a current i_1, the magnetic force H at a point P in the plane bisecting the element at right angles will be in this plane and at right angles to the line joining P to the element. If x be the distance of P from the element we have, by Laplace's formula,

$$F = \frac{l_1 i_1}{x^2}$$

Thus the magnetic flux ϕ linked with a small conductor of length l_2 parallel to the element is given by

$$\phi = l_1 l_2 i_1 \int_x^\infty \frac{1}{x^2} \partial x$$
$$= \frac{l_1 l_2}{x} i_1.$$

Hence if $i_1 = I \sin \omega t$, the disturbing E.M.F. e' is given by

$$e' = \frac{\partial \phi}{\partial t} = \frac{l_1 l_2 \omega I}{x} \cos \omega t$$
$$= \frac{2\pi l_1 l_2 u I}{\lambda x} \cos \omega t \quad . \quad . \quad (14)$$

The disturbing E.M.F. therefore varies inversely as λ and as x.

Let us now consider an infinitely long horizontal wire carrying a current i_1. If a plane circular circuit of radius r be in the same plane as the wire and if its centre be at a distance x from the wire, we know that

$$L_{12} = 4\pi\{x - \sqrt{(x^2 - r^2)}\} \quad . \quad . \quad . \quad (15)^*$$

exactly.

If x be large compared with r, then

$$L_{12} = \frac{2A_2}{x} \text{ (approx.)} \quad . \quad . \quad . \quad . \quad (16)$$

* A. Russell: "Alternating Currents," vol. 1, p. 53.

where A_2 is the area of the circle. In general, if A_2 be the area of a small circuit with its plane in the same plane as the wire, then, whatever its shape,

$$L_{12} = \frac{2A_2}{x} \text{ (approx.)} \quad . \quad . \quad . \quad . \quad (17)$$

Let us now suppose that we have a parallel return wire in the same horizontal plane as the first wire and the circuit A_2, and that the distance between the wires is c. Equation (17) now becomes

$$L_{12} = \frac{2A_2}{x} - \frac{2A_2}{x+c} = \frac{2cA_2}{x^2} \text{ (approx.)} \quad . \quad (18)$$

The effect now falls off inversely as the square of the distance. This formula may easily be generalized by theorems given in Russell's "Alternating Currents," vol. 1, chap. 19. Let A_2 be the area of a small circuit of any shape with its plane parallel to the wires and at a great distance x from them. If x makes an angle θ with the plane of the wires, and the plane of the small circuit makes an angle ϕ with the same plane, we can easily show that

$$L_{12} = \frac{2cA_2}{x^2} \cos (2\theta - \phi)^* \quad . \quad . \quad . \quad (19)$$

Let the values of x supposed drawn in a vertical plane perpendicular to the wires from the mid-point between the two wires be plotted out so that at their extremities the magnetic effects produced are the same (L_{12} constant). We have

$$x^2 = \frac{2cA_2}{L_{12}} \cos (2\theta - \phi).$$

If we suppose that ϕ is a constant (zero for instance) we see that the curve is a lemniscate. Radio engineers have a hankering after this curve in connection with the explanation of effects noticed in directive signalling.

Let us next consider two small plane circuits of areas A_1 and A_2 at a great distance x apart. If both circuits are in the same plane, we have

$$L_{12} = \frac{A_1 A_2}{x^3} \text{ (approx.)} \quad . \quad . \quad . \quad . \quad (20)$$

If they are both vertical and opposite one another,

$$L_{12} = \frac{2A_1 A_2}{x^3} \text{ (approx.)} \quad . \quad . \quad . \quad . \quad (21)$$

In general, if the planes of the two circuits make angles θ_1 and θ_2 with x and with x produced, respectively, we have

$$L_{12} = \frac{A_1 A_2}{x^3}\{2 \sin \theta_1 \sin \theta_2 + \cos \theta_1 \cos \theta_2\} \quad (22)$$

If θ_1 remain constant and θ_2 vary, the maximum value of L_{12} is given by

$$(L_{12})_{\max.} = \frac{A_1 A_2}{x^3}\{1 + 3 \sin^2 \theta_1\}^{\frac{1}{2}}$$

Keeping this value of L_{12} constant we get the polar equation to the curve of equal magnetic effect. Simi-

* Notice that when ϕ equals 2θ, L_{12} has its maximum value, and that it vanishes when $\phi = 2\theta - \frac{1}{2}\pi$.

larly, if the planes of A_1 and A_2 are perpendicular to one another ($\theta_2 = 0$) we get

$$x^3 = \frac{A_1 A_2}{L_{12}} \sin \theta_1$$

and if L_{12} is kept constant we get a new polar curve.

Three-Phase Circuits.

It is known that the electrostatic and electromagnetic fields round three-phase circuits sometimes cause interference. It is of importance therefore to consider them. Let us suppose that the axes of the three conductors form the edges of an equilateral prism. Let also the edges be at a distance a from the central line of the prism. Suppose that the currents in the three conductors are $I \sin \omega t$, $I \sin (\omega t - 120°)$ and $I \sin (\omega t - 240°)$. Then if R be the magnetic force at a point P at a great distance x from the central line of the prism, in the direction of x, and T be the tangential force perpendicular to x, we have,* approximately,

$$R = \frac{3aI}{x^2} \sin (\omega t - \theta) \text{ and } T = \frac{3aI}{x^2} \cos (\omega t - \theta) \quad . \quad (23)$$

Thus the magnetic field at P is a rotary field, and therefore the induced E.M.F. in a small circuit whose plane is parallel to the edges of the prism is the same whatever angle it makes with x.

If we had a single-phase circuit consisting of two parallel wires at a distance c apart, then the radial and tangential components of the magnetic force would, by (19), be given by

$$R = \frac{2cI \sin \omega t}{x^2} \sin \theta ; \text{ and } T = \frac{2cI \sin \omega t}{x^2} \cos \theta \quad (24)$$

where $I \sin \omega t$ is the current in the wire and θ is the angle that x makes with the plane of the wires. If $c = 1 \cdot 5a$ it will be seen that the amplitude of the magnetic effects produced would be the same in the two cases. With single-phase circuits the fields are purely oscillatory.

Similarly in the three-phase case it can be shown that the electrostatic field at a distant point P is a rotating one, and that the magnitude of the resultant electric force at P is $3aQ/x^2$, where Q is the maximum value of the electric charge per unit length on each of the three-phase conductors. If f is the frequency of the alternating currents the angular velocities of the rotating electric and magnetic fields at P each equal $2\pi f$.

When the three-phase system is connected in "star" and the star points are connected to another conductor we get a four-wire three-phase system. The disturbing effects are now greatly increased. Let i_1, i_2 and i_3 be the currents in the three conductors. In this case $i_1 + i_2 + i_3$ is not necessarily zero, although the effective values of each of the currents may be the same. The tangential magnetic force at a point P at a great distance x has therefore a component

$$\frac{2(i_1 + i_2 + i_3)}{x}.$$

* A. Russell: "Alternating Currents," vol. 1, p. 478.

Similarly it has a component

$$- \frac{2(i_1 + i_2 + i_3)}{y}$$

where y is the distance of P from the return-conductor.

If $y = x + d$, the tangential magnetic force T is approximately given by

$$T = \frac{2d(i_1 + i_2 + i_3)}{x^2}$$

and the mutual induction between the four-wire system and a small horizontal circuit of area A_2 at P is given by

$$L_{12} = \frac{2dA_2}{x^2}$$

and the induced E.M.F. e' in this circuit is given by

$$e' = \frac{2dA_2}{x^2} \cdot \frac{\partial}{\partial t} (i_1 + i_2 + i_3) \quad . \quad . \quad . \quad (25)$$

Now it is known * that the frequencies of the components into which the current $(i_1 + i_2 + i_3)$ may be divided are $3f$, $9f$, $15f$, . . . $3(2n + 1)f$, . . . In practice, several of these frequencies come within the range of audibility, and disturbing humming noises may ensue in neighbouring telephone circuits.

In this case also the electric force at P will have high-frequency components, and these can produce serious interference.

If the three-phase system be earthed at both ends the earth forms the fourth conductor and the interference will probably be worse than if a fourth wire were used. In a three-wire three-phase system when one of the conductors is out of commission the system reduces to a single-phase system and so the effects can be computed in the way we used previously.

Conclusion.

It will be seen that we have only given approximate solutions for a few simple cases. Yet if these solutions be compared with experimental results interesting conclusions will probably be inferred. We want more experimental data on the effect of the conductivity of the earth on induction. Seeing that this conductivity varies with moisture it should not be difficult to get instructive results.

We have not discussed the problem of what happens to a communication circuit when a current surge occurs in a neighbouring power line. A definite amount of electric power is transferred to the communication circuit, and so possible damage may result. O. Brauns † has stated that when the amount of energy exceeds the hundredth part of a volt-coulomb (joule) dangerous conditions may arise. It seems to me, however, that it must depend on the rate at which the energy is delivered. I can see no justification for a general theorem of this nature.

* A. Russell: "Alternating Currents," vol. 1, p. 370.
† *E.T.Z.*, 1920, vol. 41, p. 604.

APPENDIX.

The Mutual-Capacity Coefficient of Two Spheres.

If we have two insulated conductors in infinite space and their charges per unit length are q_1 and q_2, and their potentials v_1 and v_2, the following two equations hold :—

$$q_1 = k_{11} v_1 + k_{12} v_2$$

and

$$q_2 = k_{22} v_2 + k_{12} v_1,$$

where k_{11}, k_{22} and k_{12} are geometrical constants which are difficult to calculate although sometimes easy to measure. These quantities are called capacity coefficients and attempts have been made for over a hundred years to calculate them. Only in the case of two spheres have satisfactory solutions been found.*

If we earth the second conductor ($v_2 = 0$) then the current i_2 in the earthing wire is given by

$$i_2 = -\frac{\partial q_2}{\partial t} = -k_{12}\frac{\partial v_1}{\partial t}.$$

Hence the inductive interference depends on the value of k_{12}, which is called the mutual-capacity coefficient.

* A. Russell: *Proceedings of the Royal Society*, 1920, vol. 97, p. 160.

If the radii of the spheres be a and b, and c be the distance between their centres, it can easily be shown by Poisson's method (*Memoires de l'Institut*, 1812) that

$$-k_{12} = \frac{ab}{c} + \frac{a^2b^2}{c(c^2-a^2-b^2)} + \frac{a^3b^3}{c\{(c^2-a^2-b^2)^2-a^2b^2\}} + \cdots$$

and many other formulæ for k_{12} have been found. When c is great it will be seen that this value of k_{12} is in agreement with the formulæ (6) and (7) given above.

The quickest way of obtaining the numerical value of k_{12} is to utilize the following theorem * :—

The mutual-induction coefficient between two spheres whose radii are a and b, the distance between their centres being c, equals the mutual-induction coefficient between two equal spheres the radius of each of which is $(ab)^{\frac{1}{2}}\{1 - (a-b)^2/c^2\}^{\frac{1}{2}}$ and the distance between the centres of which is $c\{1 - (a-b)^2/c^2\}$. Tables for this case have been given by Kelvin ("Reprint," p. 96) and by A. Russell (*Proceedings of the Royal Society*, 1909, vol. 82, p. 529; and *Journal I.E.E.*, 1912, vol. 48, p. 257).

* See *Proceedings of the Royal Society*, 1920, vol. 97, p. 166.

NOTE ON POLYPHASE HIGH-FREQUENCY ALTERNATORS.*

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Section 1.

Polyphase high-frequency alternators should find many practical applications. As an example, they might be employed with a group of antennæ for the purpose of directive transmission. Each phase of the alternator supplies a high-frequency current to one of the antennæ placed at a certain definite distance apart. For example, a three-phase alternator would be employed for supplying high-frequency currents to three antennæ separated by a distance equal to $\frac{1}{3}\lambda$. It is easily seen that the radiation from such a set of antennæ has a directive characteristic; in one direction the radiation will be very strong, while in others it will be feeble. The interchanging of any two of the three phases in such a set will permit of sending in the opposite direction.

It is well known that, in the ordinary type of machines for a given speed and voltage, polyphase machines can develop a greater output than single-phase machines of the same size, the reason being that the armature periphery is better utilized. Also for high-frequency alternators, when the tooth widths in the stator and the rotor are suitably chosen so as to bear a certain relation to each other, we arrive at the conclusion that the utilization of the armature or stator periphery is inherently far better in polyphase than in single-phase machines. This is shown in the calculations given below.

Let us take the case of a homopolar high-frequency alternator provided with polyphase windings, as shown diagrammatically in Fig. 1.

Let τ_t = rotor tooth width,†

τ_s = rotor slot width,

τ = pole pitch, i.e. distance between centres of two adjacent teeth in the rotor,

$= \tau_t + \tau_s$,

τ'_t = stator tooth width,

τ'_s = stator slot width,

τ' = distance between centres of two adjacent teeth in the stator,

$= \tau'_t + \tau'_s$.

In high-frequency alternators we take

$$\tau_s = \tau_t = \tfrac{1}{2}\tau \quad . \quad . \quad . \quad . \quad . \quad (1)$$

When the peripheral speed, V, of the rotor is given, the frequency, f, of the current produced by the alternator may be expressed by

$$f = V/\tau \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The slot width and the tooth width of the rotor are then determined if this frequency f is given. The dimension of the stator slots and teeth for this polyphase alternator may be found from the relation

$$2p\tau' = (2p \pm 1)\tau \quad . \quad . \quad . \quad . \quad (3)$$

where p is the number of phases of the alternator.

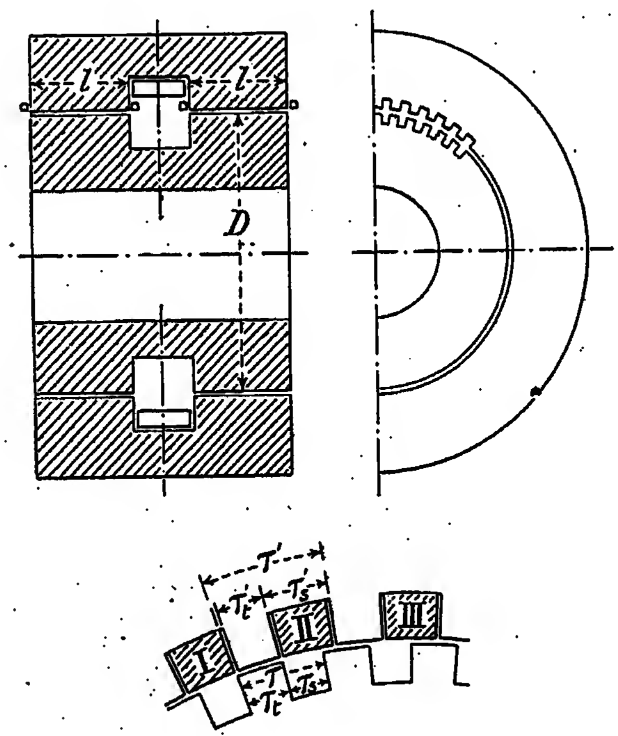

FIG. 1.

Since the number of slots n_r, n_s in the rotor and stator respectively are related to τ and τ' by the equation $n_r\tau = n_s\tau' = \pi D$, where D is the diameter of the rotor, we have, instead of (3),

$$\begin{cases} n_r = (2p \pm 1)m \\ n_s = 2pm \end{cases} \quad . \quad . \quad . \quad . \quad (4)$$

where m is any integer.

When using the relation $2p\tau' = (2p - 1)\tau$, it is preferable to choose τ'_s so that

$$\tau'_s = \tfrac{1}{2}\tau \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and
$$\tau'_t = \tau' - \tau'_s = \frac{p-1}{p} \times \frac{\tau}{2} \quad . \quad . \quad . \quad (5a)$$

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† All quantities are expressed in C.G.S. units (electromagnetic) unless otherwise stated.

If we use the relation $2p\tau' = (2p+1)\tau$, τ'_t should be chosen so that

$$\tau'_t = \tfrac{1}{2}\tau \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and
$$\tau'_s = \tau' - \tau'_t = \frac{p+1}{p} \times \frac{\tau}{2} \quad . \quad . \quad . \quad (6a)$$

(*a*) *The case when* $2p\tau' = (2p-1)\tau$.—For the sake of simplicity let us assume that in the stator teeth the flux density is zero for that part not facing the rotor teeth. We then see that the flux in stator teeth 1, 2, 3, . . . p, . . . $2p$ (Fig. 2) is

$$\frac{p-1}{p}B_m l\tau_t,\ \frac{p-2}{p}B_m l\tau_t, \ldots$$
$$\frac{1}{p}B_m l\tau_t,\ 0,\ 0,\ \frac{1}{p}B_m l\tau_t \ldots \frac{p-1}{p}B_m l\tau_t \quad . \quad (7)$$

where B_m is the maximum flux density in the air-gap, and l is the axial length of the slots (see Fig. 1).

The flux between the two conductors, 1–1, of the same phase is then

$$\left(\frac{p-1}{p} + \frac{p-2}{p} + \frac{p-3}{p} + \ldots + 0\right)B_m l\tau_t$$

When the rotor moves by the amount $\frac{1}{p} \times \frac{\tau}{2}$, this flux becomes

$$\left(\frac{p-2}{p} + \frac{p-3}{p} + \ldots + 0 + 0\right)B_m l\tau_t$$

and with another displacement $\frac{1}{p} \times \frac{\tau}{2}$ of the rotor it becomes

$$\left(\frac{p-3}{p} + \frac{p-4}{p} + \ldots + 0 + \frac{1}{p}\right)B_m l\tau_t$$

and so on.

Hence we see that the minimum value of this flux is

$$\phi_1 = \left(\frac{q}{p} + \frac{q-1}{p} + \frac{q-2}{p} + \ldots \right.$$
$$\left. + 0 + 0 + \frac{1}{p} + \frac{2}{p} + \ldots + \frac{q-1}{p}\right)B_m l\tau_t$$
$$= \left\{2\left(0 + \frac{1}{p} + \frac{2}{p} + \ldots + \frac{q-1}{p}\right) + \frac{q}{p}\right\}B_m l\tau_t$$

when $p = 2q + 1$ (odd)

$$\phi_1 = \left(\frac{q-1}{p} + \frac{q-2}{p} + \ldots \right.$$
$$\left. + 0 + 0 + \frac{1}{p} + \frac{2}{p} + \ldots + \frac{q-1}{p}\right)B_m l\tau_t$$
$$= 2\left(0 + \frac{1}{p} + \frac{2}{p} + \ldots + \frac{q-1}{p}\right)B_m l\tau_t$$

when $p = 2q$ (even)

If from this position of minimum flux the rotor be displaced by the amount $\frac{1}{2}\tau$, we obtain the maximum value

$$\phi_2 = \left\{2\left(\frac{q+1}{p} + \frac{q+2}{p} + \ldots + \frac{p-1}{p}\right) + \frac{q}{p}\right\}B_m \tau l_t$$

(when $p = 2q + 1$)

$$\phi_2 = 2\left(\frac{q}{p} + \frac{q+1}{p} + \frac{q+2}{p} + \ldots + \frac{p-1}{p}\right)B_m l\tau_t$$

(when $p = 2q$)

The difference between the maximum and minimum values is

$$\phi_m = \phi_2 - \phi_1 = \frac{2(p-q)q}{p}B_m l\tau_t \quad (8)$$

and in both cases $p = 2q + 1$ and $p = 2q$.

Now consider the conductors 1–1 which interlink this flux. We see that the loop "ab" formed by these conductors links the maximum flux $\phi_2 - \phi_1 = \phi_m$ at a certain position of the rotor. After the rotor has been displaced by $\frac{1}{2}\tau$ the loop is interlinked by the same amount of the flux ϕ_m but in the opposite direction.

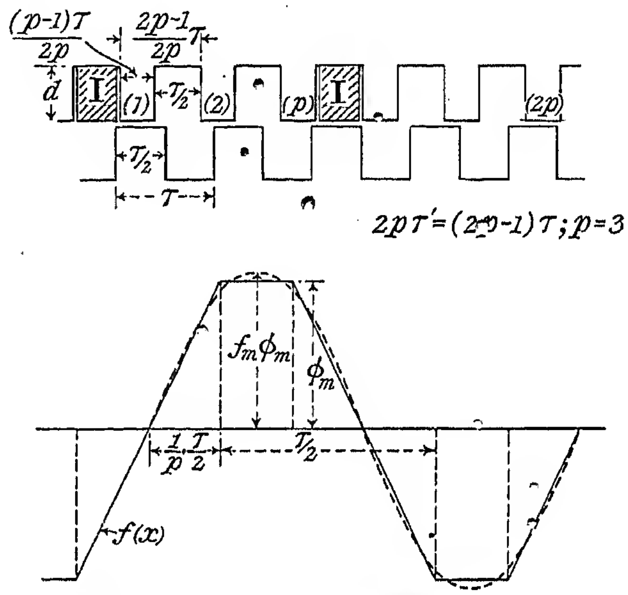

FIG. 2.

Between these two positions the flux changes in the manner shown in Fig. 2. This graph is obtained by plotting the values of the flux corresponding to every displacement $\tau/(2p)$ of the rotor. Considering only the fundamental of this curve, we can express the wave-form of the flux by

$$f_w\phi_m \sin\left(\frac{2\pi}{\tau}x\right) = f_w\phi_m \sin\left(\frac{2\pi}{\tau}Vt\right)$$
$$= f_w\phi_m \sin 2\pi f t$$
$$= f_w\phi_m \sin \omega t$$

where f_w is the ratio of the amplitude of the fundamental harmonic to the maximum amplitude ϕ_m of this flux $f(x)$.

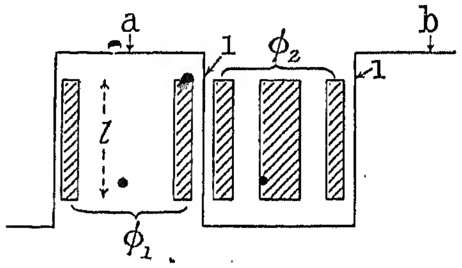

FIG. 3.

Hence the E.M.F. induced in the loop "ab" is

$$e_{ab} = \frac{d}{dt}(f_w\phi_m \sin\omega t)10^{-8} = \omega f_w\phi_m \cos\omega t \times 10^{-8}$$
$$= \omega f_w \frac{2(p-q)q}{p}B_m l\tau_t \cos\omega t \times 10^{-8} \text{ volts} \quad (9)$$

The number of the conductors in the stator periphery is

$$n_s = \frac{\pi D}{\tau'} = \pi D \frac{2p}{(2p-1)\tau}$$

and

$$\frac{n_s}{p} = \frac{2\pi D}{(2p-1)\tau} \text{ per phase} \quad . \quad . \quad . \quad (10)$$

Therefore the E.M.F. induced in one half of the stator is

$$e_{AB} = \frac{n_s}{2p} e_{ab} = \frac{2\pi D}{(2p-1)\tau} \times \frac{(p-q)q}{p} w f_w B_m l \tau_t \cos \omega t \times 10^{-8}$$

$$= \frac{\pi D}{(2p-1)} \times \frac{(p-q)q}{p} w f_w B_m l \cos \omega t \times 10^{-8} \text{ volts}$$

Since the stator is composed of two parts (see Figs. 1 and 4) and the conductors of the same phase in these

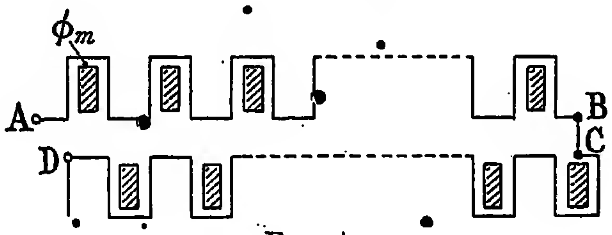

FIG. 4.

half parts are connected in series so that their induced E.M.F.'s are added, we have

$$e_{AD} = 2e_{AB} = \frac{2\pi D}{(2p-1)} \times \frac{(p-q)q}{p} w f_w B_m l \cos \omega t \times 10^{-8} \text{ volts} \quad . \quad (11)$$

E.M.F.'s of the same magnitude will be induced in the coils formed by the conductors 2–2, 3–3, 4–4,

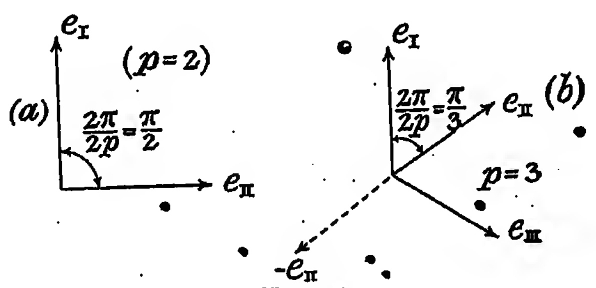

FIG. 5.

etc. But it can be seen from Fig. 2 that the E.M.F. induced in the conductors 2–2 lags behind the induced E.M.F. in the conductors 1–1 by the angle $(2\pi)/(2p) = \pi/p$, and the E.M.F. in 3–3 by the angle $2(2\pi)/(2p) = 2(\pi/p)$, and so on. When p is less than 3, these E.M.F.'s constitute p-phase voltages in the ordinary sense of the words. For example, when $p = 2$ the E.M.F.'s are related as shown in Fig. 5. When $p = 3$ the E.M.F.'s can be represented as in Fig. 5 (b), and become symmetrical polyphase E.M.F.'s if the terminals of the E.M.F. e_{II} are reversed.

When p is greater than 3, these E.M.F.'s are no longer symmetrical p-phase voltages, since the phase angle between them is now π/p instead of $2\pi/p$. The machine may be termed a $2p$-phase machine, as the E.M.F.'s e_1, e_2, e_3 . . . in one half of the stator, together with the E.M.F.'s e_1', e_2', e_3' . . . in the other half, constitute $2p$-phase voltages. In such cases we can, however, obtain symmetrical p-phase voltages if we connect the conductors in series in such a manner that the E.M.F.'s e_1 and e_2, e_3 and e_4, e_5 and e_6, etc., are added as shown in the vector diagram, Fig. 6. Hence instead of (11) we shall have

$$e_{AD} = \frac{2\pi D}{(2p-1)} \times \frac{(p-q)q}{p} w f_w B_m l \cos \frac{\pi}{2p} \cos \omega t \times 10^{-8} \text{ volts} \quad . \quad (11a)$$

when $p > 3$.

When there are currents in the stator slots, the M.M.F.'s due to these currents will modify the distribution of the flux. The induced E.M.F. on load will be different from the induced E.M.F. on no load, both in magnitude and in its phase relation to the position of the rotor. This reaction of the stator current will be considered later. For the time being we

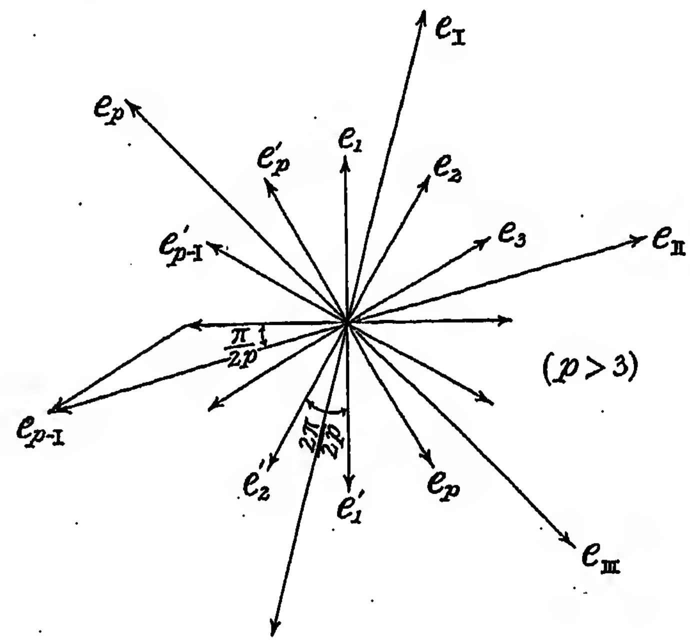

FIG. 6.

shall suppose that the induced E.M.F. remains the same independent of the load.

As the current is generally adjusted to be in phase with the induced E.M.F., we have

$$i = \delta d(\tau_s' - e) \cos \omega t = \frac{\delta d}{2} \tau (1 - \sigma) \cos \omega t \text{ (amperes)} \quad . \quad (12)$$

where δ = current density in the conductor (amps./cm²),
d = depth of the stator slot,
e = twice the thickness of insulation on the conductor,
$\sigma = 2e/\tau$.

When $p < 3$ the power developed is

$$\frac{1}{T}\int_0^{2\pi/\omega = T} e_{AD} i dt = \frac{\pi D}{(2p-1)} \times \frac{(p-q)q}{4p} (1-\sigma) w f_w (B_m \delta) d l \tau \times 10^{-8} \text{ watts per phase,}$$

and the total power of this machine will be

$$P = \frac{p}{T}\int_0^T e_{AD} i dt = \pi D \frac{(p-q)q}{4(2p-1)} (1-\sigma) w f_w (B_m \delta) d l \tau \times 10^{-8} \text{ watts} \quad . \quad (13)$$

The power output per unit length of the stator periphery is

$$\frac{P}{\pi D} = \frac{(p-q)q}{4(2p-1)}(1-\sigma)\omega f_w(B_m\delta)dl\tau \times 10^{-8}$$
$$= kf_w(B_m\delta)dl\tau f \times 10^{-8} = kf_w(B_m\delta)dlV \times 10^{-8} \text{ watts per cm} \quad . \quad (14)$$

where $$k = \tfrac{1}{2}\pi\frac{(p-q)q}{(2p-1)}(1-\sigma) \quad . \quad . \quad . \quad (15)$$

and $p = 2q + 1$ or $p = 2q$.

From (11*a*) we see that when $p<3$ this factor k becomes

$$k = \tfrac{1}{2}\pi\frac{(p-q)q}{(2p-1)}(1-\sigma)\cos\frac{\pi}{2p} \quad . \quad . \quad (15a)$$

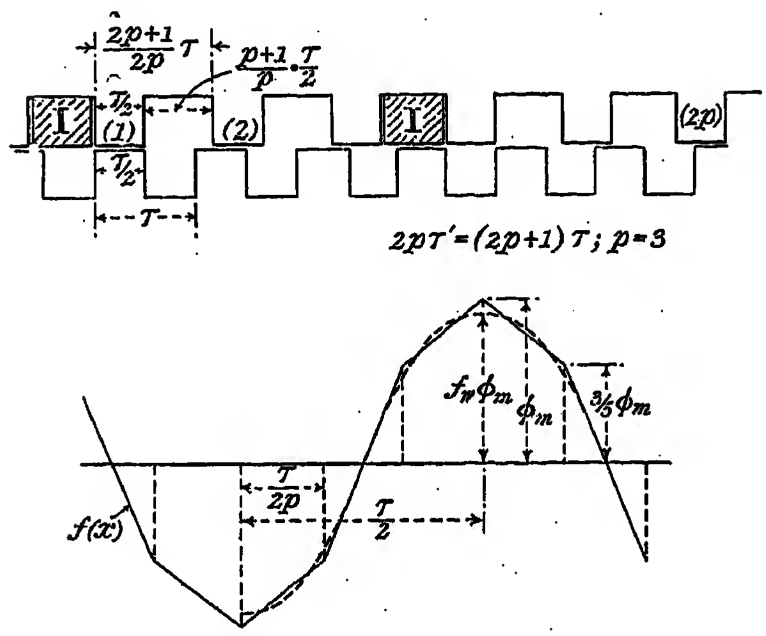

FIG. 7.

(*b*) *The case when* $2p\tau' = (2p+1)\tau$.—The flux in stator teeth 1, 2, 3, . . . p, . . . $2p$ is

$$B_ml\tau_t,\ \frac{p-1}{p}B_ml\tau_t,\ \frac{p-2}{p}B_ml\tau_t \ldots$$
$$\frac{1}{p}B_ml\tau_t,\ 0,\ \frac{1}{p}B_ml\tau_t,\ \frac{2}{p}B_ml\tau_t \ldots \frac{p-1}{p}B_ml\tau_t$$

at the instant shown in Fig. 7.

The minimum value of the flux passing between two conductors 1–1 of the same phase is

$$\phi_1 = \left\{0 + 2\left(\frac{1}{p}+\frac{2}{p}+\ldots+\frac{q}{p}\right)\right\}B_ml\tau_t \quad \text{(when } p = 2q+1)$$

$$\phi_1 = \left\{0 + 2\left(\frac{1}{p}+\frac{2}{p}+\ldots+\frac{q-1}{p}\right)+\frac{q}{p}\right\}B_ml\tau_t \quad \text{(when } p = 2q)$$

The maximum value of this flux will be

$$\phi_2 = \left\{2\left(\frac{q+1}{p}+\frac{q+2}{p}+\ldots+\frac{p-1}{p}\right)+1\right\}B_ml\tau_t \quad \text{(when } p = 2q+1)$$

$$\phi_2 = \left\{\frac{q}{p} + 2\left(\frac{q+1}{p}+\frac{q+2}{p}+\ldots+\frac{p-1}{p}\right)+1\right\}B_ml\tau_t \quad \text{(when } p = 2q)$$

Hence the difference between these two values is

$$\phi_m = \phi_2 - \phi_1 = \left\{1+\frac{2q^2}{p}\right\}B_ml\tau_t \text{ (when } p = 2q+1)$$
$$= \left\{1+\frac{2q(q-1)}{p}\right\}B_ml\tau_t \text{ (when } p = 2q) \quad . \quad . \quad (16)$$

We can now proceed as in the previous case. The calculation for $p = 2q + 1$ is given below.

When $p<3$ the E.M.F. induced in one loop is

$$e_{ab} = wf_w\left\{1+\frac{2q^2}{p}\right\}B_ml\tau_t\cos\omega t \times 10^{-8} \text{ volts} \quad . \quad (17)$$

The number of conductors per phase in the stator periphery

$$\frac{n_s}{p} = \frac{2\pi D}{(2p+1)\tau} \quad . \quad . \quad . \quad . \quad (18)$$

The induced E.M.F. of one phase is, when $p < 3$,

$$e_{AD} = \frac{n_s}{p}e_{ab} = \frac{\pi D}{(2p+1)}\left\{1+\frac{2q^2}{p}\right\}wf_wB_ml\cos\omega t \times 10^{-8} \text{ volts} \quad . \quad (19)$$

The current in the conductor

$$i = \delta d(\tau_s' - e)\cos\omega t$$
$$= \frac{p+1}{p}\delta d\frac{\tau}{2}\left(1-\frac{p}{p+1}\sigma\right)\cos\omega t \text{ amperes} \quad . \quad (20)$$

The total power

$$P = \frac{p}{T}\int_0^T e_{AD}i\,dt = \tfrac{1}{4}\pi D\frac{(p+1)}{(2p+1)}\left\{1+\frac{2q^2}{p}\right\}\left(1-\frac{p+1}{p}\sigma\right)wf_w(B_m\delta)dl\tau \times 10^{-8} \text{ watts} \quad . \quad (21)$$

The power output per unit length of the stator periphery

$$\left.\begin{aligned}\frac{P}{\pi D} &= \frac{p+1}{4(2p+1)}\left\{1+\frac{2q^2}{p}\right\}\left(1-\frac{p}{p+1}\sigma\right)wf_w(B_m\delta)dl\tau \times 10^{-8}\\ &= kf_w(B_m\delta)dlV \times 10^{-8} \text{ watts per cm}\end{aligned}\right\} \quad . \quad (22)$$

where

$$k = \tfrac{1}{2}\pi\frac{(p+1)}{(2p+1)}\left\{1+\frac{2q^2}{p}\right\}\left(1-\frac{p}{p+1}\sigma\right) \quad \text{(when } p = 2q+1) \quad . \quad (23)$$

From (16) we see that this factor k becomes

$$k = \tfrac{1}{2}\pi\frac{(p+1)}{(2p+1)}\left\{1+\frac{2q(q-1)}{p}\right\}\left(1-\frac{p}{p+1}\sigma\right) \quad \text{(when } p = 2q) \quad . \quad . \quad (23a)$$

When $p>3$, we have, instead of (23) and (23*a*),

$$k = \tfrac{1}{2}\pi\frac{(p+1)}{(2p+1)}\left\{1+\frac{2q^2}{p}\right\}\left(1-\frac{p}{p+1}\sigma\right)\cos\frac{\pi}{2p} \quad \text{(when } p = 2q+1) \quad . \quad . \quad (24)$$

$$k = \tfrac{1}{2}\pi\frac{(p+1)}{(2p+1)}\left\{1+\frac{2q(q-1)}{p}\right\}\left(1-\frac{p}{p+1}\sigma\right)\cos\frac{\pi}{2p} \quad \text{(when } p = 2q) \quad . \quad . \quad (24a)$$

Section 2.

It will be seen from the calculations given in the preceding section that for the machine of given dimen-

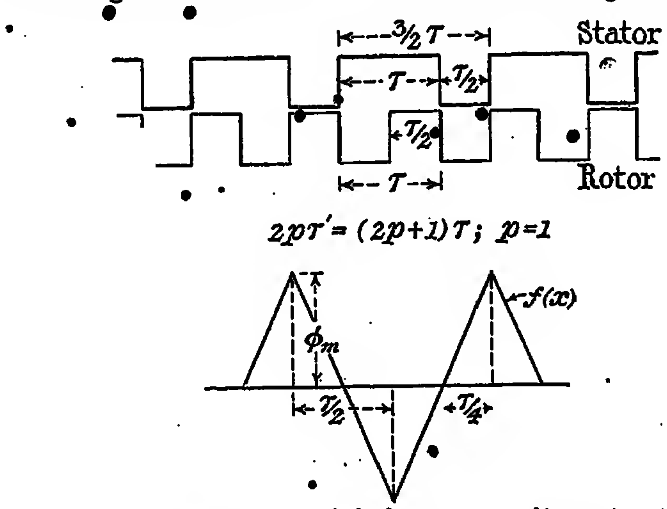

FIG. 8.—Single-phase high-frequency alternator (Société Française Radio-Electrique type).

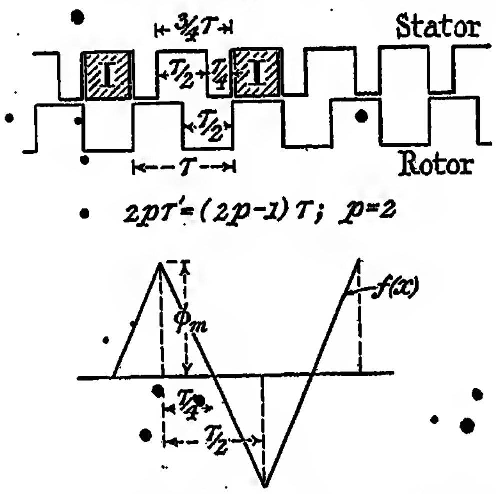

FIG. 9.—Two-phase high-frequency alternator (Latour).

sion with B_m, δ and V fixed, the relative power output may be compared by means of the factor kf_w. In Table 1 these values are given for different values of p. The value of k is calculated by means of one of the formulæ (15), (15a), (23) or (23a), and (24), (24a) for two cases. In the first case we take $\sigma = 0$, i.e. neglect the thickness of insulation on the conductor; in the second case we take $\sigma = 0\cdot1$. The factor f_w

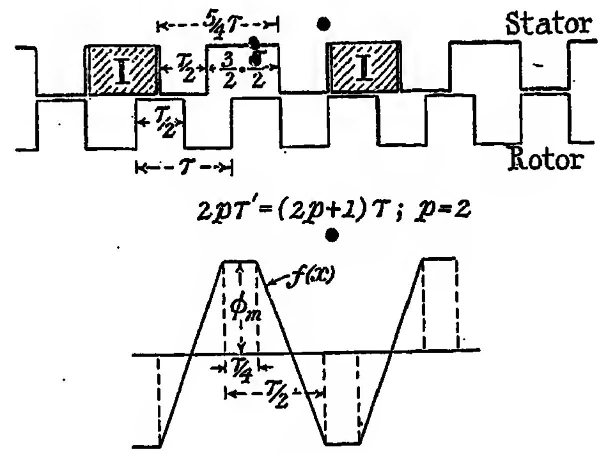

FIG. 10.—Two-phase high-frequency alternator.

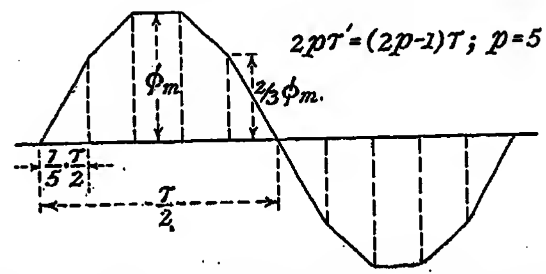

FIG. 11.—$f(x)$ curve for five-phase high-frequency alternator.

given in this table can be easily calculated if the wave-form $f(x)$ of the flux is known.

The table shows that kf_w increases steadily with p. But the number of phases cannot be indefinitely increased in practice, for τ is actually very small in

TABLE 1.

p	$2p\tau' = (2p\pm1)\tau$	f_w	k		$f_w k$		Remarks
			$\sigma = 0$	$\sigma = 0\cdot1$	$\sigma = 0$	$\sigma = 0\cdot1$	
1	$2\tau' = 3\tau$	$\frac{8}{\pi^2} = 0\cdot81$	1·05	0·995	0·85	0·807	Fig. 8
2	$4\tau' = 3\tau$	$\frac{8}{\pi^2} = 0\cdot81$	1·05	0·945	0·85	0·765	Fig. 9
	$4\tau' = 5\tau$	$\frac{8\sqrt{2}}{\pi^2} = 1\cdot14$	0·94	0·875	1·07	0·995	Fig. 10
3	$6\tau' = 5\tau$	$\frac{6\sqrt{3}}{\pi^2} = 1\cdot05$	1·26	1·13	1·32	1·19	Fig. 2
	$6\tau' = 7\tau$	$\frac{48}{5\pi^2} = 0\cdot98$	1·49	1·38	1·45	1·34	Fig. 7
5	$10\tau' = 9\tau$	1·03	1·98	1·78	2·04	1·83	Fig. 11
	$10\tau' = 11\tau$	1·00 (approx.)	2·10	1·92	2·10	1·92	—
6	$12\tau' = 11\tau$	1·00 (approx.)	2·48	2·23	2·48	2·23	—
	$12\tau' = 13\tau$	1·00 (approx.)	2·46	2·24	2·46	2·24	—

the case of high-frequency alternators and it will be a very difficult matter to construct machines which accurately satisfy the relations

$$2p\tau' = (2p - 1)\tau \quad \text{and} \quad \tau_s' = \tfrac{1}{2}\tau$$
$$\text{or} \quad 2p\tau' = (2p + 1)\tau \quad \text{and} \quad \tau_t' = \tfrac{1}{2}\tau$$

as p increases. The least discrepancy from these conditions for the widths of teeth and slots in both the stator and the rotor will greatly decrease the output of the machine. But if a lower frequency will suffice, we can take a larger value of τ. In such case a five-

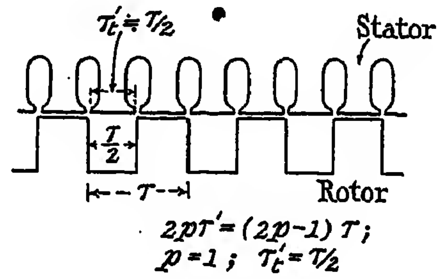

FIG. 12.

phase or six-phase alternator will be of interest, especially the latter which can be used as a three-phase machine. In order to raise the frequency, frequency-changers of saturated iron core may be employed in combination with the alternator.

There is another difficulty in the way of increasing indefinitely the number of phases p. The length of the end connection of conductors will increase, and this means an increase in the volume of copper not actually used in the production of power. At the same time the copper loss increases and the heat dissipation becomes worse. Thus we shall be obliged to reduce the value of δ which was supposed to be constant. Hence we cannot expect to obtain as great an output for large values of p as that indicated by the coefficient kf_w calculated on the simple assumption that δ is constant.

It is to be noted that when $p = 1$ in the case of $2p\tau' = (2p + 1)\tau$, this polyphase alternator reduces to the single-phase high-frequency machine of the S.F.R.* type. The two-phase machine of the type $2p\tau' = (2p - 1)\tau$ has already been proposed and described by Latour in his paper* on the high-frequency alternator of the S.F.R. type.

In the above we have taken the relation

$$\tau_s' = \tfrac{1}{2}\tau, \text{ when } 2p\tau' = (2p - 1)\tau$$
$$\tau_t' = \tfrac{1}{2}\tau, \text{ when } 2p\tau' = (2p + 1)\tau$$

But we can also imagine polyphase machines in which τ_s' or τ_t' is

$$\tau_t' = \tfrac{1}{2}\tau, \text{ when } 2p\tau' = (2p - 1)\tau \quad \ldots \quad (25)$$
$$\tau_s' = \tfrac{1}{2}\tau, \text{ when } 2p\tau' = (2p + 1)\tau \quad \ldots \quad (25a)$$

Calculations of kf_w in these cases show that these types cannot develop as much power as the others. It may here be mentioned that ordinary single-phase homopolar machines may be considered as machines of class (25) (see Fig. 12).

We shall next consider briefly the flux variation in the stator and rotor teeth. The flux variation in the

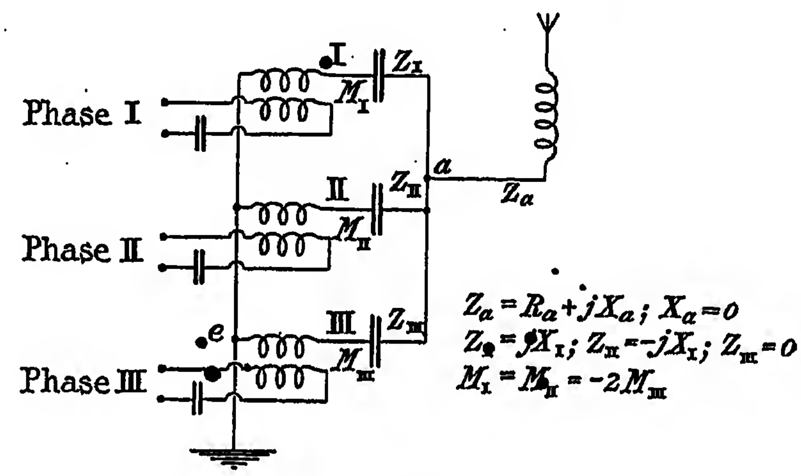

FIG. 14.

stator has a frequency f. Since we have, from (4), the relation $n_s = 2pn_r/(2p \pm 1)$, we see that the flux variation in the rotor teeth has a frequency $2pf/(2p + 1)$ or $2pf/(2p - 1)$, according as $2p\tau' = (2p + 1)\tau$ or $(2p - 1)\tau$. Take, for example, the three-phase alternator of type $6\tau' = 5\tau$. If we suppose, for the sake of simplicity, that the flux density is uniform over the whole cross-section of the teeth—the condition which holds approximately at the bottom of these teeth—then the variation of the flux density in one tooth may be represented by Fig. 13 (a). In this case the frequency of the flux-change in the stator is f, while that in the rotor is $6f/5$.

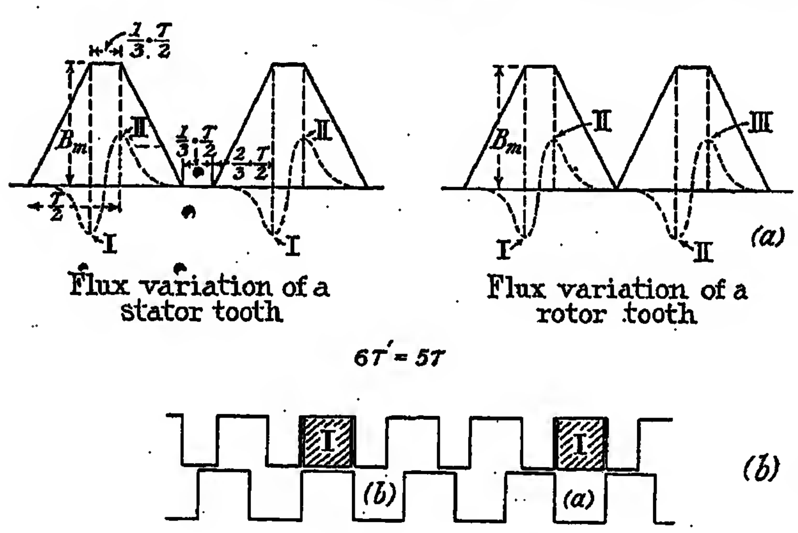

FIG. 13.

In addition to these variations there are the flux variations due to the M.M.F.'s of currents in the slots. When the current is in phase with the induced E.M.F., the stator and the rotor of this three-phase alternator will take the position shown in Fig. 13 (b) at the moment when the current of phase I is a maximum. It is seen that the effect of the M.M.F. due to this current is far greater for a tooth at (a) than for a tooth at (b). Neglecting this reaction of the current on the tooth flux when the teeth are at positions such as (b), the flux-change in the stator and rotor teeth will be somewhat similar to that represented by dotted lines in

* Société Française Radio-Electrique.

* *Radio Review*, 1921, vol. 2, p. 403.

Fig. 13 (*a*). So long as the teeth are supposed not saturated, this flux variation due to the current has no influence on the magnitude of the induced E.M.F., but it will retard its phase to a slight extent. When the current component is in quadrature with the induced E.M.F., the magnitude of the E.M.F. will change at the same time.

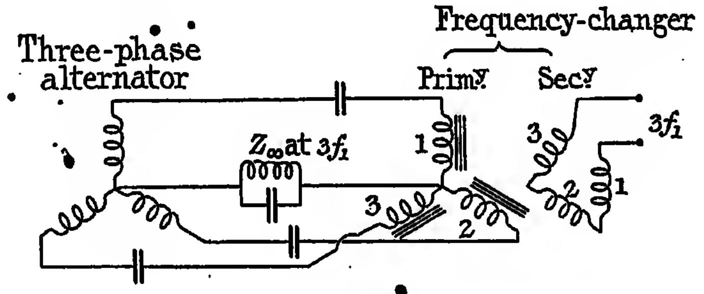

FIG. 15.

We have taken here the case of a three-phase alternator as an example for considering the flux variation in the stator and the rotor. When p becomes greater, this flux variation will be more complicated, especially when p is an odd number. In that case all the teeth in the stator or the rotor will not undergo the same flux variation.

Polyphase machines may also be used for ordinary antennæ. By a certain disposition the polyphase energy can be converted into single-phase energy.* In Fig. 14, the voltages of a three-phase alternator are impressed on the primaries of transformers I, II and III. If the coefficients of mutual inductance of these transformers and of the impedances Z_{I}, Z_{II}, Z_{III} and Z_a are suitably chosen, it is possible to make each phase of the alternator give the same current and power. If we suppose that the circuits aIe, aIIe and aIIIe have no resistance, the conditions for the balanced working of the alternator are as indicated in Fig. 14. It is also assumed here that the primaries of the transformers I, II and III have the same coefficient of self-induction, and that their circuits are adjusted in resonance with the frequency of the alternator.

Polyphase machines are especially adapted to the production of current of higher frequency. To illustrate this, let us take a three-phase alternator supplying three-phase current to the primaries of three frequency-transformers having saturated iron cores (Fig. 15). If the secondaries are correctly connected the voltages of the fundamental frequency disappear completely, but the third-harmonic voltages add together. Thus a current having a frequency three times that of the fundamental may be utilized in the secondary circuit. As the induced E.M.F. in the secondary of such frequency-transformer contains the fifth harmonic in addition to the third, a similar disposition may be adopted for a five-phase alternator to obtain the fifth-harmonic current.

APPENDIX.

Since this paper was written, the author has found that three-phase high-frequency alternators have already been invented by Frank.* Such machines are diagrammatically represented in Figs. 16, 17 and 18. The stator and rotor pitches have the following relations :—

$$\sigma\tau' = 4\tau \quad \text{(Fig. 16)}$$
$$\sigma\tau' = 2\tau \quad \text{(Figs. 17 and 18)}$$

if we adopt the same symbols.

By a method similar to that described in the present paper, the factors k and f_w can be easily calculated for these machines. Let us assume the same maximum flux density B_m in the air-gap (which means a higher density in the stator teeth than was assumed for the machines dealt with in the paper) and the same current

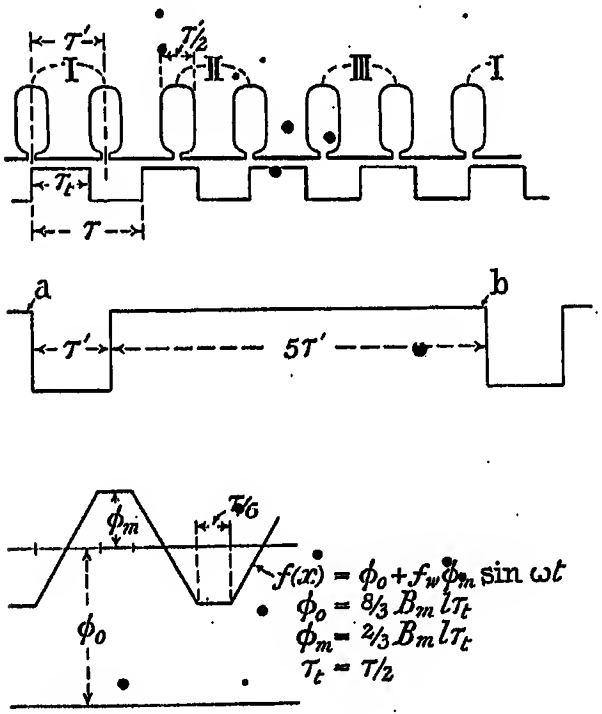

FIG. 16.

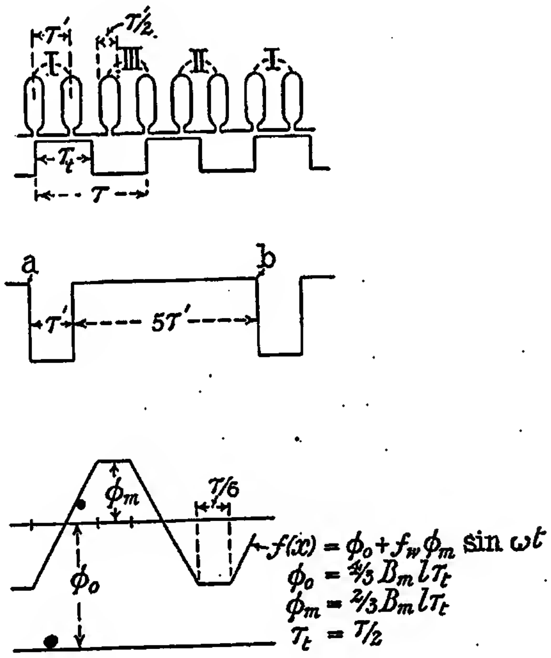

FIG. 17.

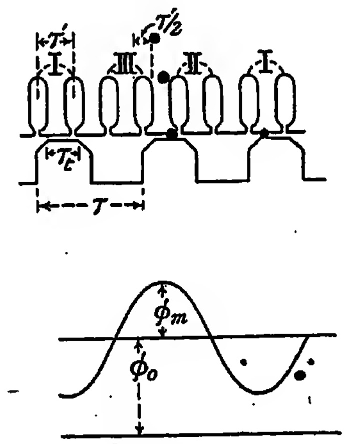

FIG. 18.

* The method adopted in the case of a two-phase alternator is described in Latour's paper (*loc. cit.*).

* *Jahrbuch der drahtlosen Telegraphie*, 1923, vol. 22, p. 44.

density δ. If we take the width of the coil to be equal to half the stator pitch, and neglect the thickness of insulation, we get

$$k = \frac{\pi}{\sigma} = 0\cdot524;\ f_w = \frac{\sigma\sqrt{3}}{\pi^2} = 1\cdot05$$

and
$$kf_w = \frac{\sqrt{3}}{\pi} = 0\cdot550$$

Even the machine in Fig. 12 is better than these machines from the point of view of utilization of the stator periphery, since kf_w is greater.*

This is because the conductors of the same phase in these machines are not arranged at equal distances, so that the flux curve $f(x)$ contains a large amount of constant and idle flux ϕ_0 with relatively small variable and useful flux ϕ_m. The inventor claims that the form of the rotor shown in Fig. 18 improves the wave-shape, but the power developed by the machine is not increased.

* $k = \pi/4 = 0\cdot785$: $f_w = 8/\pi^2 = 0\cdot81$: and $kf_w = 2/\pi = 0\cdot635$.

ELECTRICAL SIGNALLING EQUIPMENT ON RAILWAYS.

By V. Mitchell, Student.

(Abstract *of paper read before the* North Midland Students' Section, 29*th January*, 1924.)

Summary.

This paper is intended, not to give a detailed consideration of a subject upon which it is difficult to theorize, but rather to bring to the notice of engineers, who are mostly engaged on high-power plants, the achievements of a little-known department of all railway companies, the object of the department being to protect moving and stationary vehicles. The paper gives a very brief description of the evolution of the lock-and-block system of signalling and the uses of the track circuit as now employed on the Midland section of the London, Midland and Scottish Railway.

Ordinary Block System.

The expression "block system" may be defined as "A method whereby the traffic on a railroad is so regulated that only one train or vehicle occupies any one section of the line at the same time." To effect this the system must be divided into sections, each section to be termed a "block section."

Under the Regulation of Railways Act, 1899, the adoption of this system by all companies was made obligatory.

The principle of block working is well known; electrical indicators are provided to guide the signalman in the manipulation of the mechanical signals, which in their turn are provided for the guidance of engine drivers.

Three-Wire Single-Needle Block.

This was the first type of instrument used for the operation of the ordinary block; each instrument is capable of giving three indications, i.e. "line blocked" (normal position), "line clear" and "train on line." The signalman in charge of the disposal of the train can, by a single-stroke bell, call the signalman ahead, and by arranged signals inquire if the section ahead is unoccupied; if so, the signalman ahead (by a mechanical arrangement) gives the signalman in charge of the train the indication "line clear." On the train entering the section ahead the indication "train on line" is given. By this arrangement the signalman can tell the state of the section ahead and controls his mechanical signals accordingly.

Interlocking.

The arrangement just considered cannot be said to provide any additional safety for the train, the signalman still being able to work his mechanical signals irrespective of the block indications. This was soon realized, and it was decided to interlock the electrical indicators and the mechanical signals.

The requirements of an interlocking system are :—

(1) That the starting signal must not be lowered until "line clear" is given from the section ahead.

(2) That on placing the block indicator to "train on line" it is locked in that position until the train has passed through the section.

(3) That the signalman can at any time put his signals to danger.

(4) That the starter must be replaced before the indicator can be moved to "line clear."

Single-Needle Interlocking Block.

This was an improvement on the first type mentioned. On moving the indicator to "line clear" an electrical lock on the starting signal in the rear is liberated. On moving the indicator to "train on line" the instrument is locked in that position until the train passes over a contact maker under the rails, inside the home signal. Mechanical arrangements were made to comply with clauses (3) and (4).

Rotary Interlocking Block.

The interlocking block had now brought some degree of protection for the train; this was carried still further by the introduction of the rotary interlocking block. "line clear" position owing to a deviation, or otherwise, of the train concerned. This is obtained by both signalmen simultaneously pressing a cancel button, which picks up a "line clear" cancel lock in the instrument

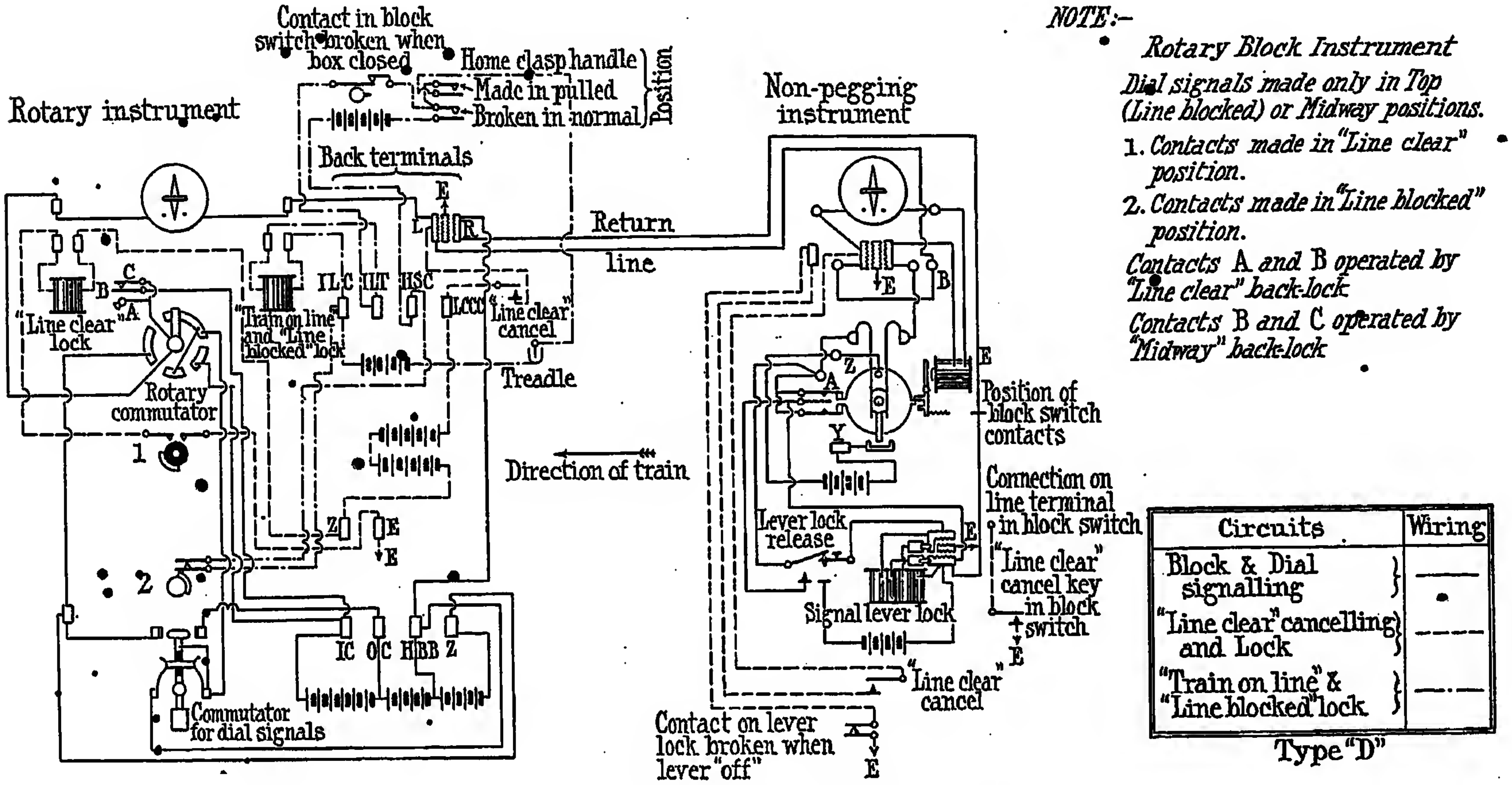

Fig. 1.—Rotary interlocking block.

A complete description of the instrument and the functions of the different parts cannot be given, but much information can be gained from Fig. 1. The indicating handle was changed to a commutator which,

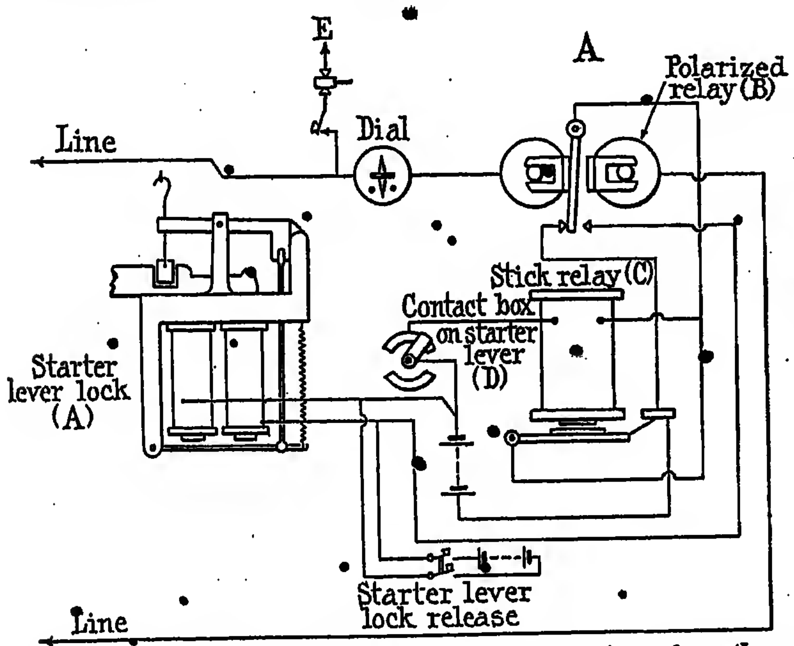

Fig. 2.—Rotary interlocking block; connections for relay working.

except in the "line clear" position, would only rotate in one direction, thus compelling the signalman to carry out the functions in correct sequence. A co-operative cancel is provided should the signalman require to take his handle back to normal from the and allows the signalman to move his handle to the normal position. Cancels are provided to obtain release should the contact maker or treadle fail to pick up the "train on line" lock on the passage of the train through the section; to obtain release the signalman must break a glass cover over the cancel key, which must afterwards be sealed up by the lineman.

A recent addition to the rotary interlocking block is the relay rotary block which is designed for places where signal boxes are closed on Sundays, as many as five block sections being switched to form one long section, the electrical connections being shown in Fig. 2.

Track Circuit.

The methods considered have all been for the protection of moving trains and become useless if no provision is made for vehicles which may have become detached from other trains, or have been left foul inadvertently. They may be standing out of sight of a signal box round a curve, or in a dense fog or tunnel. Indication of the presence of these vehicles is given to the signalman by means of a track circuit. The rails are bonded together with iron or copper bonds to give good conductivity for current from a battery situated at one end of the bonded track. The track is insulated from the rest of the system by means of insulated joints. The battery supplies the holding current for a relay joined across the other end of the track, and this relay controls the signal protecting the track. A train or vehicle standing on the track will

provide a shunt of sufficiently low resistance to drop the relay, thereby breaking the lock circuit for the signal protecting the track. This signal cannot be pulled "off" until the vehicle or train occupying the track has moved from danger (see Fig. 3).

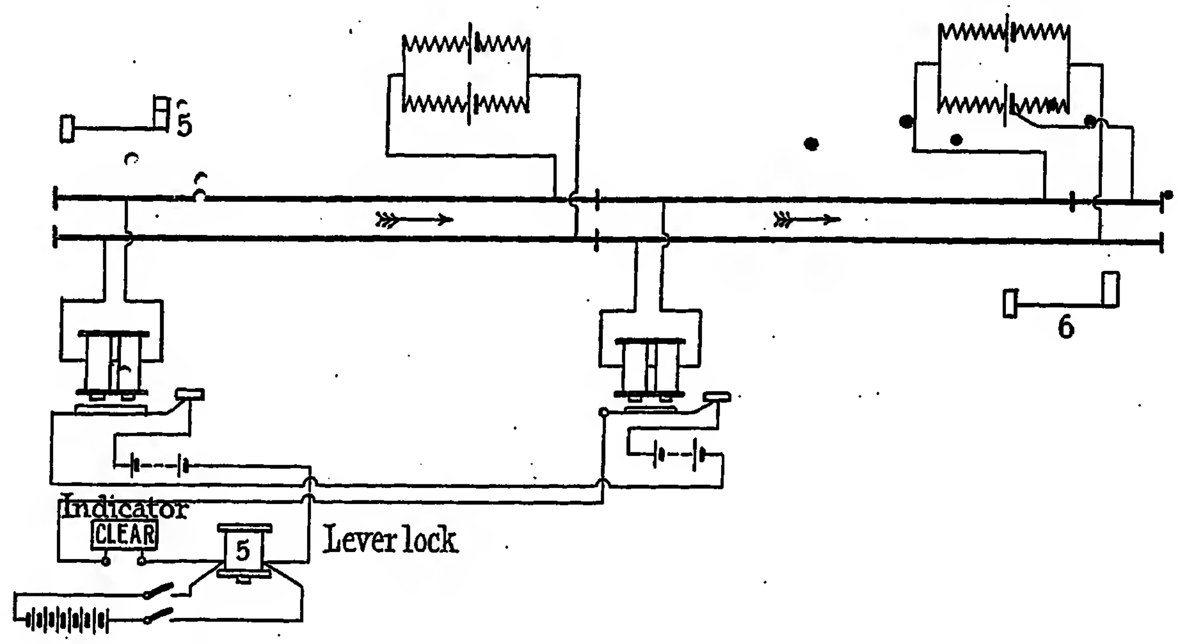

FIG. 3.—Connections for track circuit; two subsections.

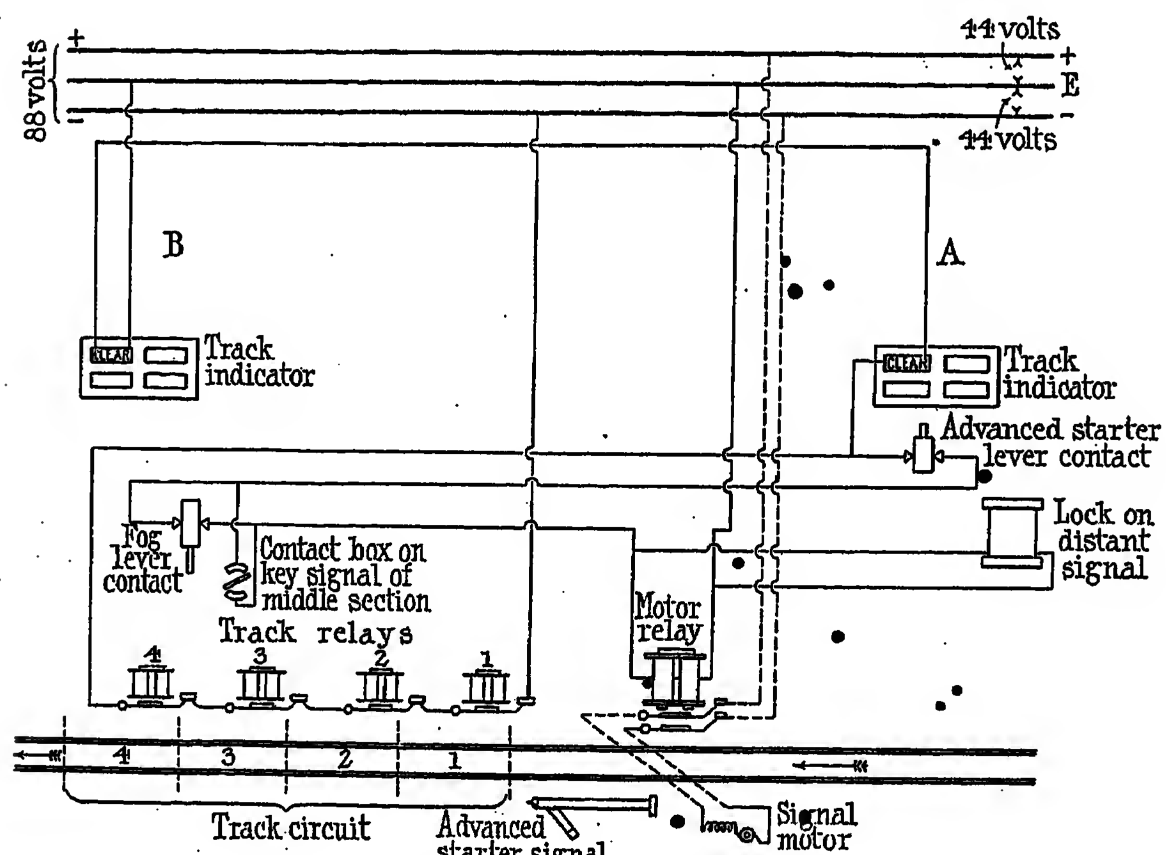

FIG. 4.—One section of semi-automatic signalling connections.

SEMI-AUTOMATIC SIGNALLING.

It was found that where long sections existed between signal boxes on busy lines, delay was caused by the length of time taken by trains to pass one at a time through the block sections. To avoid this delay the track circuit was utilized to spread out the traffic over the long section. Another block section having its own signals controlled by track circuits between two signal boxes, which can under certain conditions be controlled by the signalmen in these signal boxes, is installed, this section taking its share of the distribution of the traffic (see Fig. 4).

THE EFFECT OF THE SHAPE OF THE TRANSMITTING AERIAL UPON OBSERVED BEARINGS ON A RADIO DIRECTION-FINDER.*

By R. L. SMITH-ROSE, Ph.D., M.Sc., Associate Member.

[From the National Physical Laboratory; communicated by permission of the Radio Research Board.]

(*Paper first received 14th June, and in final form 13th August, 1924.*)

SUMMARY.

For the explanation of the variable errors encountered chiefly at night on radio direction-finders, modern theory implies the reception of waves arriving at an appreciable angle of elevation and polarized so that the magnetic field has a horizontal component in the plane of propagation. Previous experimenters have shown that such abnormally polarized waves can be radiated from certain kinds of aerials when situated at a considerable distance from the earth's surface, as in the case of an aeroplane transmitter, and that such waves when arriving at the earth's surface can produce very appreciable errors on a radio direction-finder. The experiments described in the present paper were carried out to determine to what extent the emission of these abnormally polarized waves by aerials of different shapes from a ground transmitting station was responsible for the frequent occurrence of variable "night" errors at a ground direction-finding station. It is concluded that the frequency and magnitude of these errors are independent of the shape of the transmitting aerial, within the limits of this investigation, and that the use of a source of radiation which is, as far as possible, only polarized in the normal manner, in no way diminishes the night effects generally experienced.

1. THE THEORY OF THE ERRORS OF APPARENT BEARINGS OF RADIO DIRECTION-FINDERS.

To account for the variable errors which are experienced under certain conditions in the observed bearings given by the closed-loop type of radio direction-finder, a theory was put forward by Eckersley † in 1920, which ascribed the errors to the reception of an indirect wave arriving at the receiver in a downward direction, the polarization of this wave being such that it possessed a horizontal component of magnetic field in the plane of propagation. The direct wave travels horizontally along the earth's surface and arrives at the receiver polarized with the magnetic field horizontal and at right angles to the plane of propagation.

For the purpose of clarity here and throughout the paper it is desirable to define some of the terms used in connection with the propagation of wireless waves. A wave is considered to be normally polarized when the electric force is contained in a vertical plane. The intersection of this plane with the surface of the earth is the path which is assumed to be taken by the direct wave when it is unaffected by any deviations or distortion. In a normally polarized wave, therefore, the magnetic force will always be horizontal and at right angles to the plane of propagation, whatever may be the actual direction of propagation within this plane. A closed-loop direction-finder rotating about a vertical axis will thus always indicate the true direction of arrival of such a normally polarized wave. If an error in bearing arises with such a wave, it indicates that the plane of travel of the wave is not the meridional plane between transmitter and receiver, i.e. that the wave has been subject to lateral deviation.

For an abnormally polarized wave, however, it is possible, but not necessary, that the magnetic force will have a horizontal component which is *not* at right angles to the plane of travel of the wave. In the extreme case in which the electric force is horizontal and the direction of propagation is inclined to the horizontal, the above component of magnetic force is *in* the plane of propagation. Such a wave arriving alone would evidently give a 90° error on a direction-finder and when it is received together with the direct wave the resultant horizontal magnetic field may give an error of any intermediate value from 0° to 90°, and if the phases of the two waves differ, all the effects connected with rotating fields and elliptical and circular polarization are possible.

Reception during the daytime is assumed to be carried out chiefly or entirely by the direct wave, and the errors in observed bearing on a loop rotating about a vertical axis will consequently be small. At night, however, the effect of the indirect wave is superimposed upon that of the direct wave, and, depending upon the relative magnitudes and phases of the horizontal components of their magnetic fields, errors in apparent bearings up to 90° and the common occurrences of blurred minima can be accounted for. The theory is elaborated in some detail in Eckersley's original paper, and certain experiments are described, the results of which confirm the deductions drawn from the theory.

The indirect wave arriving at the receiver in the vertical plane of propagation but inclined at an angle to the horizontal may have its origin in two causes. In the first case it may be due to the radiation from the unbalanced horizontal portions of the transmitting aerial where this is of the inverted-L type, such radiation being abnormally polarized, so that the magnetic field has a component in a vertical direction. After reflection from the lower horizontal surface of the hypothetical

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† T. L. ECKERSLEY: "The Effect of the Heaviside Layer on the Apparent Direction of Electromagnetic Waves," *Radio Review*, 1921, vol. 2, pp. 60 and 231.

Heaviside layer this wave would provide at the receiver the necessary component of horizontal magnetic field in the plane of propagation. If, however, the transmitting aerial is symmetrical about a vertical axis, then the radiation will be normally polarized. Such radiation even after reflection from the horizontal surface of an upper ionized layer will always arrive at the receiver with the magnetic field horizontal and perpendicular to the plane of propagation, and can thus never give rise to an error in apparent bearing. To explain any observed errors with the indirect wave polarized in this manner it is therefore necessary to assume that there is a change in the plane of polarization at the reflecting surface, due either to the latter not being horizontal or to some other cause.

In an article published about the same time as Eckersley's a qualitative outline of practically the same theory was given by Bellini,* from which it was concluded that the radiation from the horizontal portions of the transmitting aerial, arriving at the receiver after reflection from the Heaviside layer, would give rise to the errors in bearings experienced. The whole effect is analogous to the reception of waves transmitted from an aeroplane in such a position that it subtends an appreciable angle of elevation at the receiver. Errors in bearing arising from this cause had previously been noted by Adcock and Round,† the sign of the error depending upon the direction of travel of the aeroplane relative to the receiver, and its magnitude only reaching zero for the two cases in which the machine is flying to or from the direction-finder.

A detailed investigation of this effect of the reception of abnormally polarized waves from an aeroplane has been carried out by Baldus and Buchwald.‡ For an aeroplane at a fixed point in space they showed that the errors in apparent bearing at a ground direction-finding station varied with the orientation of the transmitting aerial and might be as great as 60° in certain cases. The magnitude and variations in the error shown by the various experiments carried out are only partially accounted for by the theoretical analysis of the problem carried out by Burstyn.§ In this calculation, however, the earth was taken as a perfect conductor, whereas some of the experiments indicated that the finite conductivity of the earth greatly affected the result.

Quantitative measurements of the intensity of the field in the radiation from an aeroplane have been carried out at a ground station by Baldus and Hase.‖ By comparing the measurements obtained on both vertical and horizontal aerials the abnormal polarization of the waves due to the shape of the aeroplane antenna was demonstrated. In the endeavour to find a form of aeroplane antenna which would eliminate the error at the ground direction-finding station, it was shown that the nearer the aerial approached the form of a vertical Hertzian oscillator the less became the magnitude of the error caused by it. Reciprocal experiments in which the strength of field from a ground transmitting station was measured in the aeroplane were made by Buchwald and Hase,* and these confirmed the shape of the characteristic radiation curves found for the L type of trailing antenna normally employed in aeroplanes.

There appears, therefore, to be experimental evidence in existence which shows: (*a*) that the arrival of an abnormally polarized wave in a direction which is not horizontal will in general give rise to an error in the bearing observed at a ground direction-finding station; and (*b*) that a type of bent-L antenna which contains an unbalanced component of horizontal current will, in free space, emit waves which are in part abnormally polarized. The experiments described in the present paper were carried out with the object of determining whether it was necessary for the waves to be abnormally polarized at the transmitter in order to give rise to the errors included in class (*a*) above.

2. Origin of Investigation and Arrangement of Experiments.

In an investigation of all the errors encountered in wireless direction-finding which has been conducted on a wide scale by the Radio Research Board since 1921, a large amount of data has been accumulated, the work of reduction of which is now well advanced. With a view to ascertaining the effect, if any, of the dimensions and shape of the transmitting aerials, details of these were sought from the authorities responsible for the respective stations whose transmissions had been used for observation purposes. Up to the time of writing, however, details have been received for the British stations only. A graphical representation of the variations in bearing experienced on those stations which have an inverted-L aerial with a long horizontal portion pointing in a known direction, shows that there is no definite relation between the direction of the receiving station relative to the transmitting aerial, and the variations in bearings experienced, whereas such an aerial should not radiate an abnormally polarized wave in its own plane. In other cases, where the transmitting aerial is known to have no unbalanced horizontal portions, very appreciable variations have been experienced during the periods of observation. Although the effects are necessarily somewhat difficult to establish with certainty, owing to the large number of other variables such as distance, geographical features, etc., which accompanied these observations, the only general conclusion which can be drawn is that no evidence is supplied that the errors or variations in observed bearings are in any way dependent upon the radiation of abnormally polarized waves from the transmitter. These observations were made on wave-lengths from 2 to 10 km, employing both damped and undamped waves.

The present experiments originated in a suggestion made by Prof. G. W. O. Howe in 1920 to Committee C of the Radio Research Board, that an experimental transmitting station should be set up at which the conformation of the aerial could be altered and its effect

* E. Bellini: "The Errors of Direction-Finders," *Electrician*, 1921, vol. 86, p. 220.

† H. J. Round: "Direction and Position Finding," *Journal I.E.E.*, 1920, vol. 58, p. 236.

‡ R. Baldus and E. Buchwald: "Experiments on the Wireless Orientation of Aeroplanes," *Jahrbuch der drahtlosen Telegraphie*, 1920, vol. 15, p. 214.

§ W. Burstyn: "Wireless Telegraphy in Space," *ibid.*, 1920, vol. 16, p. 322.

‖ R. Baldus and R. Hase: "Measurement of Energy Radiated by an Aeroplane Antenna," *ibid.*, 1920, vol. 15, p. 354.

* E. Buchwald and R. Hase: "Reception Experiments in Aeroplanes," *Jahrbuch der drahtlosen Telegraphie*, 1920, vol. 15, p. 101.

upon a directional receiver at a distance could be studied. Various considerations precluded the possibility of the erection of an aerial of sufficient vertical and horizontal dimensions for the carrying out of the experiments at long wave-lengths, and 450 m was ultimately selected as the wave-length, damped waves from a spark transmitter being employed. From other observations which had been in progress for some time it was known that the effects observed would not be fundamentally different on any other wave-lengths within wide limits, nor would they differ with the use of undamped waves.

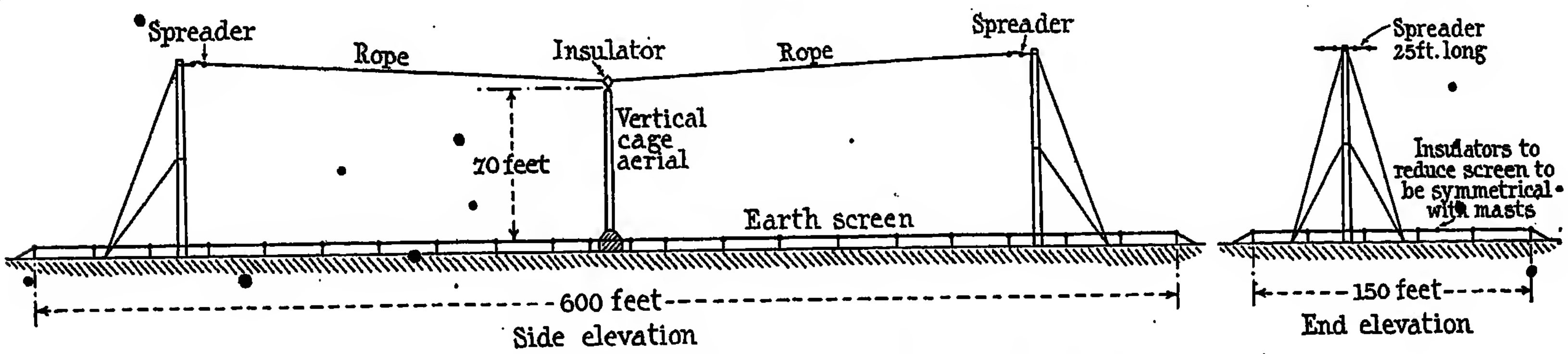

FIG. 1.—Side and end elevations of vertical-aerial arrangement.

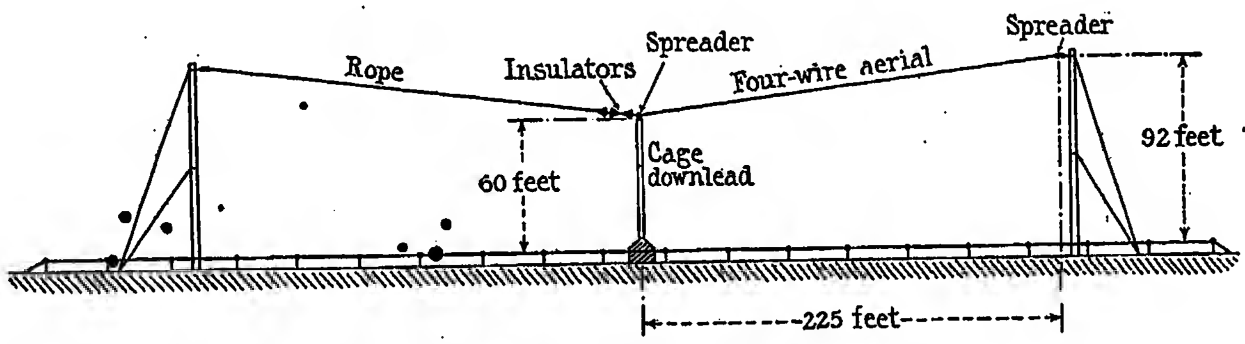

FIG. 2.—Side elevation of inverted-L aerial.

The aerial employed for these experiments at the National Physical Laboratory is slung between two wooden masts 100 ft. high and 450 ft. apart, the guy wires to these masts being split up into short lengths by porcelain insulators. The horizontal portion of the T aerial normally used is formed of four wires equally spaced on 25-ft. spreaders. An earth screen 600 ft. × 150 ft. is employed, being supported on porcelain insulators on wooden posts, the average height of the screen above the ground being about 8 ft. Owing to lack of space the masts were not situated quite symmetrically with respect to the screen, but insulators were provided in the screen wires by which the overhanging portion could be cut off, the width of the screen being thereby reduced to 100 ft.

3. Procedure of Experiments.

The general mode of procedure in this investigation was to set up one type of aerial and then make daily transmissions of special signals for two 2-hour periods, one of which was located near mid-day and the other near midnight. Observations of the apparent bearings were made on these transmissions at the two direction-finding stations at Slough and Orford, which are respectively 11·5 and 93 miles distant from Teddington. With each type of aerial employed this daily procedure was repeated for a fortnight, without making any alteration whatever, so as to obtain a fair average of the observed direction-finding conditions during both day and night periods. The transmissions from Teddington took place at 10-minute intervals and were interspersed with similar transmissions from Orford. At this station the transmitting aerial of the normal T shape was retained throughout the whole of the experiments, and the corresponding observations made at Slough afford what is in the nature of a check on the prevailing direction-finding conditions in the different periods.

The experiments were commenced with a fortnight's test made with the T aerial and the full width of the earth screen. A vertical aerial was then erected in the form of a four-wire cage of 3 ft. diagonal suspended

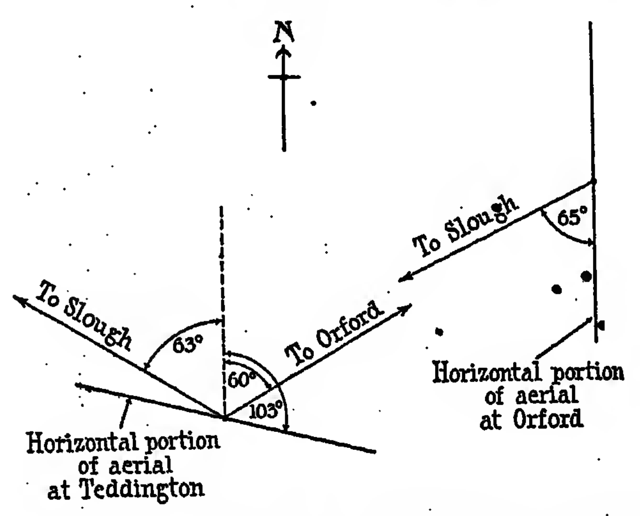

FIG. 3.—Plan of transmitting aerials relative to directions of receivers.

from the centre of two hemp ropes carried between the spreaders slung from the top of the masts. The height of this cage was about 70 ft. from the screen, and the portion above the screen was adjusted as closely vertical

TABLE 1.

*Summary of Day Observations made at Slough on the Transmissions from Orford.**

Week ending	Number of Observations	Error of Mean Bearing	Maximum Variation from Mean Bearing	Percentage Variations from Mean Bearing	
				Up to 1°	Up to 2°
		degs.	degs.	per cent	per cent
17/3/23	39	−0·9	+0·6	100·0	—
24/3/23	35	−0·6	−1·2	97·0	100·0
9/6/23	69	−1·5	+2·7	93·0	100·0
16/6/23	39	−2·4	−1·9	90·0	100·0
23/6/23	42	−1·9	+2·1	81·0	100·0
28/7/23	28	−1·2	+1·2	96·5	100·0
4/8/23	41	−1·4	−2·9	78·0	97·6
22/9/23	53	−0·9	−1·4	90·6	100·0
29/9/23	52	−0·8	−1·5	98·1	100·0

* True bearing of Orford at Slough = 65·3°.

TABLE 2.

*Summary of Night Observations made at Slough on the Transmissions from Orford.**

Week ending	Number of Observations	Error of Mean Bearing	Maximum Variation from Mean Bearing	Percentage and Cause of Missed Bearings		Percentage Variations from Mean Bearing			
				Absence of Minimum	Wandering Minimum	Up to 1°	Up to 2°	Up to 5°	Up to 10°
		degs.	degs.	per cent	per cent	per cent	per cent	per cent	per cent
17/3/23	90	− 4·5	−20·8	20·0	6·7	2·2	6·7	51·1	66·7
24/3/23	71	− 5·5	−34·8	31·0	8·5	—	2·8	15·5	50·7
9/6/23	29	− 1·7	−22·6	51·8	24·1	—	6·9	13·8	17·2
16/6/23	30	− 2·0	+11·7	33·3	3·3	36·7	56·6	60·0	60·0
23/6/23	33	+ 2·4	+22·3	48·5	12·1	3·0	3·0	21·2	30·3
28/7/23	39	+10·5	−45·8	48·7	12·8	—	—	—	7·7
4/8/23	47	− 2·8	−32·5	68·1	8·5	2·1	4·3	8·5	8·5
22/9/23	44	− 5·5	−14·8	47·7	20·5	—	4·5	11·4	29·6
29/9/23	49	− 2·7	−17·6	42·9	8·2	10·2	28·6	47·0	47·0

* True bearing of Orford at Slough = 65·3°.

TABLE 3.

*Summary of all Observations made at Slough on the Transmissions from Teddington.**

Week ending	Aerial used	No. of Observations	Error of Mean Bearing	Max. Variation from Mean Bearing
			degs.	degs.
17/3/23	T	132	+3·4	−0·5
24/3/23	T	127	+3·6	+0·7
9/6/23	Vertical	120	+3·9	±0·7
16/6/23	Vertical	77	+4·0	+0·9
23/6/23	Vertical	82	+3·7	+0·8
28/7/23	Free end to E.	100	+3·4	+0·7
4/8/23	Free end to E.	106	+3·4	±0·9
22/9/23	Free end to W.	118	+3·4	+1·0
29/9/23	Free end to W.	116	+3·4	+1·0

* True bearing of Teddington at Slough = 110·5°.

as possible, the lead-in to the transmitting hut being taken below the screen and being only about 4 ft. in length. An elevation of this vertical aerial arrangement is shown in Fig. 1. With this vertical aerial two tests of a fortnight's duration each were carried out, in the second of which the earth screen was reduced in width as mentioned above. This arrangement provided exact symmetry of intersection of the screen by any vertical plane through the aerial. This alteration produced no noticeable effect on the observations made at the receiver, however, and the symmetrical screen was retained in all the remaining experiments. For the inverted-L aerial, one half of the horizontal top of four wires on a 25-ft. spreader was replaced, the other half being retained as rope. The elevation of this aerial is shown in Fig. 2 from which it is seen that the ratio of horizontal spread to vertical lead is 225/92 = 2·45. After a fortnight's test with this arrangement the free end of the aerial was changed over to the other mast,

4. Summary and Discussion of Results Obtained.

Tables 1 and 2 give a summary of the observations obtained at Slough on the transmissions from Orford throughout the investigation. The results are given as weekly summaries, and the day and night periods are separated as stated. A summary of the observations of apparent bearings made at Orford upon the transmissions from Teddington throughout the whole series of experiments is given in Tables 4 and 5. The simultaneous observations made at Slough are summarized in Table 3, the day and night readings being here combined since there was no perceptible difference between them.

Considering Table 1 in the first instance, it will be seen that over the whole period of about six months' working, large numbers of observations show a comparatively small variation in apparent bearing for day transmissions. The extreme values are less than 3° different from the mean and, with one week's exception,

Table 4.

*Summary of Day Observations made at Orford on the Transmissions from Teddington.**

Week ending	Aerial used	Number of Observations	Error of Mean Bearing	Maximum Variation from Mean Bearing	Percentage Variations from Mean Bearing	
					Up to 1°	Up to 2°
			degs.	degs.	per cent	per cent
17/3/23	T	37	−3·0	+0·6	100·0	—
24/3/23	T	41	−3·1	0·0	100·0	—
2/6/23	Vertical	34	−3·0	+1·4	97·2	100·0
9/6/23	Vertical	57	−3·2	+1·6	86·0	100·0
16/6/23	Vertical	42	−3·1	±2·0	85·7	100·0
23/6/23	Vertical	33	−3·8	+1·9	48·5	100·0
28/7/23	Free end to E.	55	−2·6	+2·0	96·4	100·0
4/8/23	Free end to E.	63	−2·5	+1·9	88·9	100·0
22/9/23	Free end to W.	59	−1·8	−1·3	86·5	100·0
29/9/23	Free end to W.	58	−2·4	−1·3	98·3	100·0

* True bearing of Teddington at Orford = 240·6°.

giving the equivalent of a rotation of the inverted-L aerial through 180° in a horizontal plane. With the completion of observations on the transmission from this type of aerial, a few check readings were taken on transmissions from the original T aerial.

The horizontal portion of the aerial at Teddington was in a direction approximately 103° from true North, and the direction of Orford was 60°, so that the latter direction made an angle of 43° with the horizontal portions of the aerial. At Orford the transmitting aerial was practically due North and South, so that the direction of Slough made an angle of 65° with the horizontal portion of the aerial (see Fig. 3).

The direction-finding stations employed at Orford and Slough were of the standard Marconi-Bellini-Tosi pattern and do not call for any special comment, beyond the statement that the aerial loops were used in the untuned condition throughout.

all the observed readings differ from the mean by less than 2°. The majority of the larger variations recorded, and particularly the reduced average in the week excepted above, were due to the presence of interfering signals at the time of observation. The mean observed bearing shows an average difference of the order of 1° from the true value. Referring to Table 2 it is seen that during the corresponding night periods a totally different state of affairs prevailed. It was the general rule throughout all the periods of observation that the bearings observed were very erratic and in many cases very difficult to obtain. In actual figures it is seen that in the majority of cases a very small percentage of the observed bearings were within 2° of the mean value, and in many cases less than 25 per cent were within 5° of the mean. This greatly reduced accuracy is due to the prevalence of the well-known night conditions in direction-finding, the extreme

flatness of the signal minima and the rapidity with which the apparent bearings changed making it impossible to determine any bearing in from 26 per cent to over 76 per cent of cases.

The observations recorded in Table 3 made on transmissions over the comparatively short distance from Teddington to Slough, show that for both day and night periods the extreme variations are approaching the limits of accuracy of the direction-finding apparatus. Of the total observations made, amounting to nearly 1 000, the maximum deviation is 1°. It will be noted that in this case there is a permanent error of about 3·5° which has been shown by observations on a portable direction-finder to be due to the site of the Slough station.

type of aerial employed. The T and vertical types of aerial, which have no unbalanced horizontal currents, gave rise to errors in observed bearings ranging up to 30·7°, and during the individual weeks' tests it was impossible to obtain a bearing at all in from 43 per cent to 86 per cent of cases. During the four weeks' tests carried out with the inverted-L aerials, the errors recorded were of somewhat larger order and ranged up to 75°. It is doubtful, however, if this is very significant, as the extreme observations which give rise to this figure were taken with very large angles of swing (from 80° to 140°). These figures make the readings very unreliable, and the observations would probably have been better classed with the "no minimum" variety. It should also be noted that the extent of

TABLE 5.

*Summary of Night Observations made at Orford on the Transmissions from Teddington.**

Week ending	Aerial used	Number of Observations	Error of Mean Bearing	Maximum Variation from Mean Bearing	Percentage and cause of missed bearings		Percentage Variations from Mean Bearing			
					Absence of Minimum	Wandering Minimum	Up to 1°	Up to 2°	Up to 5°	Up to 10°
			degs.	degs.	per cent	per cent	per cent	per cent	per cent	per cent
17/3/23	T	91	−1·9	+11·3	55·0	28·6	0·0	14·3	14·3	14·3
24/3/23	T	83	−3·1	− 2·5	69·9	15·7	13·3	13·3	13·3	13·3
2/6/23	Vertical	31	−1·8	+ 5·7	54·8	—	3·2	29·0	38·7	45·2
9/6/23	Vertical	52	−2·2	+11·6	44·2	—	9·6	26·9	44·2	53·8
16/6/23	Vertical	36	−3·8	+ 6·2	47·2	—	25·0	36·1	50·0	52·8
23/6/23	Vertical	30	+5·1	−30·7	60·0	—	3·3	3·3	10·0	23·4
28/7/23	Free end to E.	48	+2·4	−23·0	64·6	—	0·0	8·3	16·6	29·2
4/8/23	Free end to E.	58	−2·8	†−37·8	51·7	—	3·4	5·2	22·4	25·9
22/9/23	Free end to W.	63	+8·4	‡+66·0	39·7	—	6·3	6·3	11·1	36·5
29/9/23	Free end to W.	57	+4·0	‡+75·4	50·9	—	1·7	1·7	26·3	29·8
20/10/23	T	27	+0·1	− 5·7	51·8	—	22·2	25·9	37·0	48·2
17/11/23	T	28	+2·7	+26·7	42·9	—	7·1	10·7	32·2	53·6

* True bearing of Teddington at Orford = 240·0°   † Swing of extreme readings = 80°.   ‡ Swing of extreme readings = 140°.

Reverting next to Tables 4 and 5 it is seen that the change of aerials at Teddington produces no distinctive effect on the bearings at Orford. The day readings show a total variation which is of the usual order for propagation over distances approaching 100 miles, and in every case all the readings are within 2° of the mean. The whole summary, in fact, shows a striking resemblance to the corresponding observations made in the reverse direction, viz. from Orford to Slough, and this similarity, as contrasted with the effects observed between Teddington and Slough, appears to indicate that the effects are not local to either transmitting or receiving station, but are due to some variation in conditions over the path of transmission.

In a very similar manner the readings taken during the night periods (Table 5) do not show anything distinctive which can be definitely associated with the variation of Orford's bearings at Slough vary greatly for the different weeks' summaries.

The proportion of readings recorded as missed on account of the above absence of minimum is seen to range from 40 per cent to 65 per cent for the L aerials and is thus quite comparable with the corresponding figures for the T and vertical aerials. With all the types of aerials employed it will be seen that it is comparatively seldom that more than 30 per cent of the readings are within 2° of the mean value, or more than 40 per cent within 5° of the mean.

5. CONCLUSION.

The general conclusion to be drawn from this experimental investigation is therefore that all attempts made to arrange the conformation of the transmitting aerial so as to prevent the emission of radiation polarized in such a manner that the electric field is horizontal and

magnetic field vertical, have been unsuccessful in materially reducing the occurrence of night effects encountered at a distant direction-finding station. If, therefore, Eckersley's theory of night errors is correct, the abnormally polarized component of the downcoming waves would appear to be due either to the reflecting layer not always being horizontal, or to the effect of the earth's magnetic field in causing a rotation of the plane of polarization of the waves on reflection at the upper ionized layer.*

It should be remarked that the intensity of this reflected wave must quite often be greater than that of the direct wave, for it was frequently observed during the tests that the strength of signal in the maximum position of the search coil by day was less than the strength at night when the coil was perpendicular to this. Fading of the received signals at Orford was also noted with all the aerials employed at Teddington.

* See T. L. Eckersley: *loc. cit.*, p. 239; also W. H. Eccles: Chairman's Address to Wireless Section, *Journal I.E.E.*, 1921, vol. 59, p. 82.

These experiments were carried out for the Radio Research Board under the direction of the Committee on Directional Wireless, the members of this Committee being as follows:—Mr. F. E. Smith, C.B.E., F.R.S. (*Chairman*); Mr. F. W. Davey; Mr. C. E. Horton, B.A.; Capt. C. T. Hughes, M.C., R.E.; Dr. J. Robinson, M.B.E.; Dr. G. C. Simpson, F.R.S.; Dr. R. L. Smith-Rose; and Mr. O. F. Brown, M.A., B.Sc. (*Secretary*).

The author wishes to acknowledge the valuable services rendered during this investigation by the following assistants:—Petty Officer R. Taylor and Telegraphist G. A. Williams, at Orford; Messrs. R. H. Barfield, M.Sc., S. R. Chapman, B.Sc., and M. G. Bennett, B.Sc., at Slough; and Messrs. E. L. Hatcher and A. C. Haxton, at Teddington.

THE NATURE AND REPRODUCTION OF SPEECH SOUNDS (VOWELS).

By Sir Richard Paget, Bart.

(*Lecture delivered before* The Institution, *20th March*, 1924.)

Human speech forms in a special degree a bond between the physicist and the electrical engineer. Take, for example, the question of the range of human speech. The gibbon can be heard at a range of six miles, whereas under the best natural conditions the range of human speech is only of the order of half a mile. By the art of the telephone engineer, however, the balance has been handsomely redressed, and, in America, the human voice has been heard by cable at a distance of over 5 000 miles, while by wireless telephony transatlantic conversation is beginning to be possible.

The amazing development of the telephone, and of cabled and wireless transmission of speech, has been produced to a large extent without any very close investigation of the mechanism by which the sounds were originally produced. But now, especially in the hands of the Western Electric Company of America, refined analysis of the nature of speech sounds is being made. A more intimate knowledge of the human acoustic mechanism may be of assistance to the electrical engineer, besides affording to the physicist a little relaxation in the course of his strenuous pursuit of the electron.

The first scientific explanation of the differences between the vowel sounds was that given by Willis, of Cambridge, in 1828. Willis showed that each separate vowel sound depended on a characteristic resonance set up in the human mouth. He also reproduced a number of vowel sounds by means of a vibrating reed (corresponding to the human vocal chords) and a tubular resonator. I will demonstrate this effect by means of a tubular resonator with a reed set in a plunger which moves up and down the tube so as to vary the vowel sound produced when air is blown through the reed.

About 1834 Wheatstone at King's College, London, made his talking machine—on the lines of one previously made (about 1760–1770) by de Kempelen, but with various improvements. In this device (exhibited by the courtesy of King's College) Willis's tubular resonator is replaced by a cup-shaped cavity and the vowel sounds are produced by covering the orifice by the hand so as to vary its aperture.

In the sixties of last century Helmholtz further developed Willis's theory, but added the observation that some vowel sounds depended on two characteristic resonances set up in the vocal cavity. He also devised the Helmholtz resonator. The late Lord Rayleigh clarified the whole subject of the resonance of a cavity which was small in comparison with the wave-length of its natural resonance, and he even investigated mathematically the behaviour of two Helmholtz resonators joined in series. The human voice appears to be entirely produced by Helmholtz resonance—not by tubular resonance of the wind-instrument type.

As illustrating the principles of Helmholtz resonators, I have here three egg-shaped resonators, their cubic capacities being 185, 70 and 30 cm^3 and the diameters

of their orifices being 25–26, 15–15·5, and 7·5–8 mm respectively. All three models shown give the same note (512 ∾) when blown as whistles by means of a rubber tube, but the larger resonators produce vibrations of greater amplitude. For this reason men, women and children, with voices of very different pitch (due to the different lengths of their vocal chords), can still speak alike, as far as pronunciation is concerned, in spite of the difference in size of their resonating cavities.

In the English language, at least, the vocal chords are not an organ of speech; they are a vehicle of speech. Practically all the essentials of the English language are found in whispered speech. [The lecturer then whispered the following: "If I put my vocal chords out of action, by separating them as in breathing, so that the air that passes through my vocal cavities is not vibrating but is merely turbulent, I can still speak so as to be understood at a moderate range." The words were clearly heard throughout the lecture hall.]

It was as if, in the beginning, man roared by nature in the open, but taught himself to whisper in the cave, and as if the essentials of language were first based on whispered sounds. Then, perhaps, came the discovery that if the whisperer roared at the same time, the roar acted as what would now be called a "carrier wave" for the whispered sounds.

This ingenious device has not yet been developed to its logical conclusion, and therefore almost all languages still consist of a jumble of voiced and unvoiced sounds. These differ enormously in carrying power.

Experiments which I have carried out with Miss Sylvia Paget show that in general the effect of voicing a vowel sound is to increase its carrying power from 10 to 20 times, as compared with the range of the corresponding whispered or unvoiced sound.

There is, I believe, only one language in which the roar and the whisper are perfectly combined—in other words, in which all the sounds are voiced—and that is the dialect of my native county of "Zummerzet." In that dialect all the sounds have a carrying power of the same order, besides all having the added beauty of musical inflection and melody. The "Zummerzet" dialect ought without doubt to become the standard form of English for all telephonic and broadcasting purposes!

In investigating the nature of human speech it is obviously simplest to start (as other investigators have done) with whispered speech.

It appears that in the case of every vowel sound the vocal cavity is producing two audible resonances. Some of these double resonances can be made audible by clapping the hands in front of the mouth, so as to drive air into it in sharp puffs and create resonance; and the upper and lower resonances can be varied independently so as to produce two scales in contrary motion.

The resonances heard in my own voice are shown in Fig. 1. It will be noticed that the two resonances of the vowel sounds e (men) and ɐ (earth) have similar intervals (measured in semitones), also æ (hat) and U (put), and that ʌ (up), ɑ (calm), ɒ (not), ɔ (all), o (know) and u (who) all have approximately the same interval between their upper and lower resonances.

This suggests that the vowels of the three series might be phonographically transformed or translated by varying the speed of the record, as has been done by Preece and Stroh (*Proceedings of the Royal Society*, A, 1879, vol. 28, p. 358) and D. C. Miller ("Science of Musical Sounds," p. 232).

I will illustrate the translation of e (men) to ɐ (earth), or æ (hat) to U (put), and of ʌ (up) to ɑ (calm), ɒ (not), ɔ (all), o (no) and u (who), by means of records of the three original vowels made on the dictaphone, the transformation being produced by appropriately reducing the speed of the revolving cylinder.

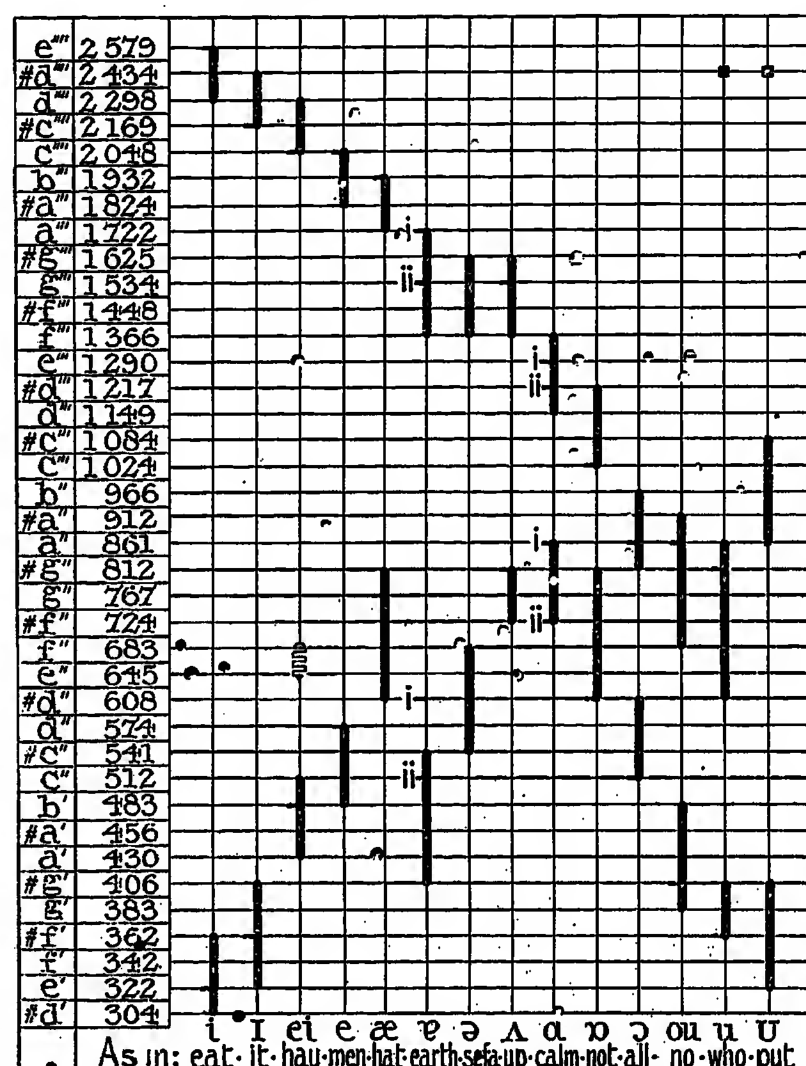

FIG. 1.—Resonances in Sir Richard Paget's voice.

Experiments with an artificial plasticine mouth show that the double resonances are produced by what are in effect two Helmholtz resonators in series, one behind the tongue and the other in front of it, the tongue operating as a movable stop of variable aperture. The two resonators are found to react on one another (as had been already indicated by Lord Rayleigh), but in the human mouth the necessary corrections are performed automatically.

I propose to blow, on Lord Rayleigh's demonstration organ (lent by the Royal Institution), plasticine resonators fitted with organ reeds and tuned to the resonances of the vowel sounds a (calm), e (men), I (it), ɔ (all) and U (who); also to blow other vowel models by mouth.

The conclusions arrived at are: (1) Whispered vowels are due to air passing through two Helmholtz resonators in series or in parallel; (2) voiced vowels

are produced by substituting vibrating air for a simple air-stream; and (3) Willis's fixed-pitch theory is confirmed.

The double-resonant character of all the English vowel sounds was published in *Nature* in March 1922. In April 1922 the idea suggested itself that these double-resonant vowel sounds might be produced electrically, by substituting electrical resonating circuits for Helmholtz resonators. Dr. Eccles promised to try the experiment. Before the opportunity occurred, however, the idea was independently evolved, and the experiment tried—with success—by Mr. John Q. Stewart in the Research Laboratory of the Western Electric Company of America.

Stewart's letter to *Nature* of July 1922 gave a diagram of his circuits (see Fig. 2) and stated:—

"Appropriate adjustments of the resonant circuits 1 and 2 were observed to result in the production of all

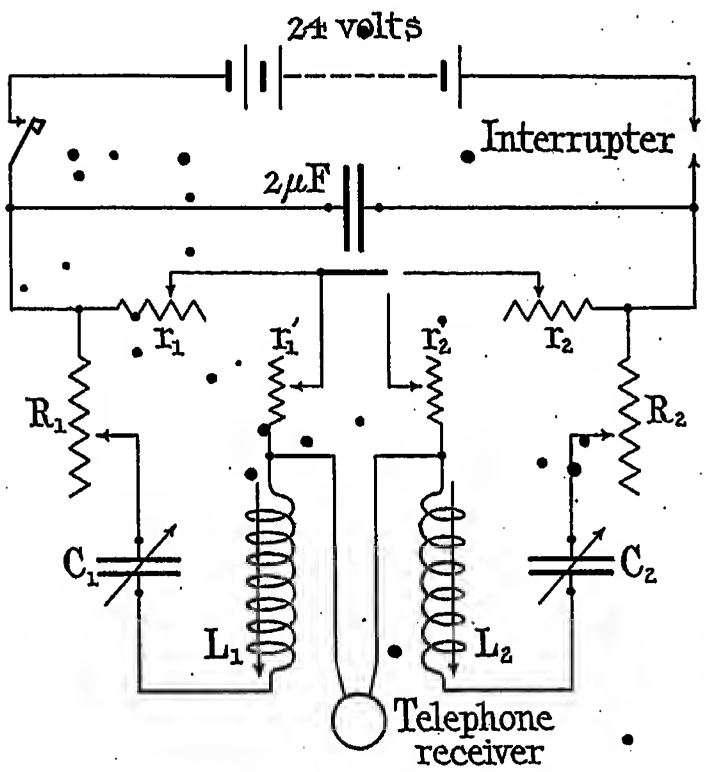

FIG. 2.—Circuit used by Mr. J. Q. Stewart.

the various vowels and semi-vowels in turn. Alteration of the frequency or damping of either resonant circuit was observed to result in alteration of the vowel produced. The frequency of interruption, which was the group frequency of the recurrent damped oscillations, was observed to determine the pitch of the vowel; but it did not determine what vowel was produced. It was found possible to produce the whispered vowels with interruptions that were non-periodic.

"The first three vowels given in this table are each characterized by a single train of recurrent damped oscillations; the remaining three are characterized by two trains of recurrent damped oscillations."

Dr. Eccles's experiment, which was first shown at the Royal Institution in 1923, differed in several interesting respects from Stewart's. In Dr. Eccles's arrangement (see Fig. 3) there were two sending circuits each of which could give six frequencies of different amounts over one million per second. The receiving circuit oscillated at one million per second and therefore sent to the loud-speaker heterodyne beats at audible frequency corresponding to the difference between one million and the two sending-station frequencies respectively. In the apparatus here shown, the interrupter which represents the "larynx" is connected to the sending circuits so that these are brought into action alternately; and persistence of audition in the human ear combines the two alternate frequencies into a single vowel-like sound. [The vowel sounds *i* (eat), ɔ (all), e (men), u (who), ɑ (calm) and ɐ (earth) were then reproduced.]

The experiments of Stewart and Eccles respectively give good confirmation of the theory of double resonance, though Stewart's apparent production of a (calm), ɔ (all), u (who) by single resonance needs explanation.

There is another respect in which a close analogy exists between the phenomena of acoustic and electrical transmission of vibratory energy—which has been pointed out by Mr. Rollo Appleyard, who wrote:—

"We are learning to think electrically. The reason for this is that the various factors that enter into calculations in electrical circuits can be more easily

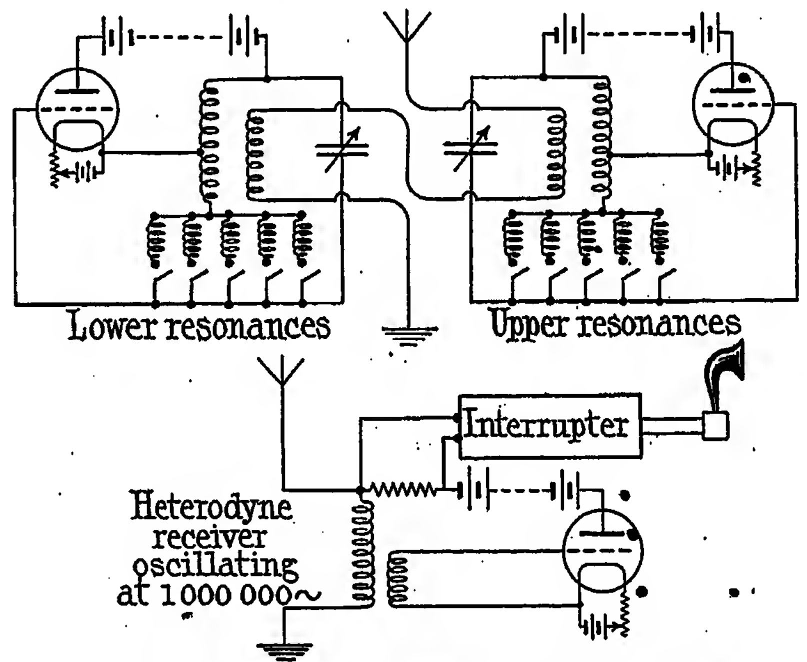

FIG. 3.—Arrangement used by Dr. W. H. Eccles.

measured, and isolated from one another, than is possible with their mechanical or acoustic analogies—when free, forced, coupled and compound vibrations are taken into account.

"Your vowel-resonators are a case in point. Their determining characteristics are, in general parlance, their shape, volume, and material. If we think electrically, however, we realize that they, their contents, and their surroundings, must be defined ultimately in terms analogous to the four cardinal attributes: resistance, inductance, capacity, and leakance. Hence, we examine them, and their associated acoustic system, for their equivalents: friction, inertia, elasticity, and slip or leakage. Further we are led to realize that these may, in some circumstances, be variables, depending upon 'frequency' and that we are consequently concerned, in our energy equations, with 'effective' values of the four cardinal attributes.

"Thanks to the work of Newton, who associated the transmission of sound with the motion of the pendulum

and gave us the earliest conception of an elastic medium through which pulsations are transmitted by successive condensations and rarefactions ("Principia," Second Part, Section VIII), thanks to the work of Lagrange ("Œuvres," vol. 1, p. 79) who solved the problem of a vibrating loaded catenary, and to the labours of Fourier, who, in 1822, taught physicists how to calculate the flow of heat along a metal bar, the way was prepared for Kelvin, Blakesley, Rayleigh, Heaviside, Pupin, Breisig, Fleming, and others to interpret the riddle of transmission, and of the attenuation of oscillatory electric currents of 'frequencies' within speech limits, through extended conductors. For any given 'frequency' the result is now clearly expressed in terms of those same four cardinals: resistance, inductance, capacity, and leakance.

"In recent years, yet another step has been taken. It is now realized that, in order that a current impulse may pass from one section of an electrical network to another, with minimum loss of energy, and with minimum distortion, the characteristics of the one section, expressed in terms of what I have here (for distinctiveness) called the four cardinals, must as nearly as possible resemble the characteristics of the other, in like terms. At a surface of transition there is energy-loss, unless the characteristics on each side of that surface are identical. At an intermediate surface of transition, there is, in general, reflection and attenuation; and at the end surface, there is, in general, reflection, to account for the energy-loss.

"May we not, by means of these energy relationships, develop a broad generalization which shall link acoustics and electrical transmission with mechanics, and thus complete the picture?

"For the telephone diaphragm the translation of energy has already been analysed by A. E. Kennelly and G. W. Pierce (see *Proceedings of the American Academy of Arts and Sciences*, 1912, vol. 48, p. 113).

"An illuminating study of the energy problem, including a summary of this work of Kennelly and Pierce, will be found in the Kelvin Lecture delivered by Professor J. A. Fleming to the Institution of Electrical Engineers on May 10, 1923."

The task of measuring the four cardinals in the case of acoustic systems, so that their performance can be predicted with the same certainty as that of their electrical analogies, offers much opportunity of useful acoustic research to the physicist.

Returning now to human speech, it is safe to affirm that the consonants are as essentially musical as the vowels—that they are also Helmholtz resonator effects—but that they differ from the vowels in being more complex and particularly in having (in many instances) components of much higher pitch than the vowels.

The consonants, or some of them, also differ from the vowels in another respect, namely, that they depend for their effects on our ears upon the rate of change of the frequency of their component resonances.

The vibration of the air in a system of resonators may be set up by a vibrating diaphragm. Thus an electrically-driven diaphragm (that of a "clear-hooter" horn) in which the horn has been replaced by a double resonator can be progressively changed so as to sound the word "away"—by varying the area of the front orifice by hand.

A variable double resonator may even be made by the operator's two hands working in conjunction with an artificial air-blown larynx of variable pitch, as in my device, the "Cheirophone."

I will blow this first by bellows to demonstrate the production of the various vowel sounds and subsequently by mouth to produce artificial speech—the latter requiring a more exact timing of the air supply.

[The names "Oliver Lodge" and "Vernon Boys" were pronounced, and the lecturer concluded with three cheers, on the Cheirophone, for "the Physical Society on the occasion of its Jubilee, not forgetting the great Institution in whose building the celebrations are being held."]

NORTHOLT RADIO STATION.

By A. C. WARREN, B.Sc., Student.

(ABSTRACT *of paper read before the* LONDON STUDENTS' SECTION, *9th May*, 1924.)

SUMMARY.

The paper gives a brief description of the equipment at the Post Office Radio Station at Northolt, near Harrow, and a survey of some of the experimental investigations which have been carried out at the station, namely :—

(*a*) The installation of a 30–40 kW valve transmitter.
(*b*) The design of a coupled circuit for the arc sets.
(*c*) Trials on a Lorenz alternator.
(*d*) Investigation into the losses occurring in transmitting inductances.
(*e*) Tests on insulating materials.

DESCRIPTION OF THE STATION.

Introductory.—The Northolt Radio Station is a medium-power telegraphic relay station capable of working a continuous service over a range of 1 000–2 000 miles at speeds up to 60 words per minute. The transmitting equipment consists of two arc sets and one valve set capable of delivering 16 and 30–40 kW respectively into the aerial. The transmission is controlled from the Central Radio Office, G.P.O. West, at which all reception is carried out.

Aerial system.—The main aerial is supported from three wooden lattice masts each 446 ft. high arranged in the form of an equilateral triangle of 650 ft. side. The lead down is taken from the centre of one side of the triangle and is led into the building through an insulator fitted in a glass window 6 ft. square. The earth system consists of copper plates and strip buried under the full area enclosed by the masts. The aerial constants are : Capacity, 7 000 $\mu\mu$F ; natural wave-length 2 000 m ; resistance 2 ohms at 6 950 m.

Power supply.—Power is obtained from the Uxbridge Power Supply Co. at 6 600 volts, three-phase, 50 periods, and is transformed down to 415 volts. Motor-generator sets giving 650 volts and 110 volts (d.c.) are provided for the main and auxiliary supplies to the arc sets. The valve set is run from the a.c. supply which is transformed up and rectified to give 8 000–18 000 volts (d.c.).

Transmitting plant.—The arc sets are of the Elwell-Poulsen type and are designed for a maximum input of 40 kW. Under working conditions the arcs are run through a coupled circuit, an input of 20–30 kW giving an aerial current of 45–55 amperes. The overall efficiency of the arcs is 25–30 per cent.

The valve set is equipped with a rectifying unit consisting of six silica valves which are fed from a three-phase transformer, three-phase full-wave rectification being employed. The oscillator unit comprises six silica valves or three water-cooled metal valves, and with the latter an output of 30 kW gives 110 aerial amperes. The overall efficiency is 50–55 per cent and the efficiency of the transmitting valves 75–80 per cent.

The normal wave-lengths of transmission are 6 950 m for the arc sets and 5 780 m for the valve set. Transmission is effected by means of marking and spacing waves, the difference between the two wave-lengths being of the order of 50 m.

OUTLINE OF THE DEVELOPMENT WORK.

Design and installation of the valve transmitter.—This work was commenced as soon as the arc sets had been installed. The design was necessarily largely experi-

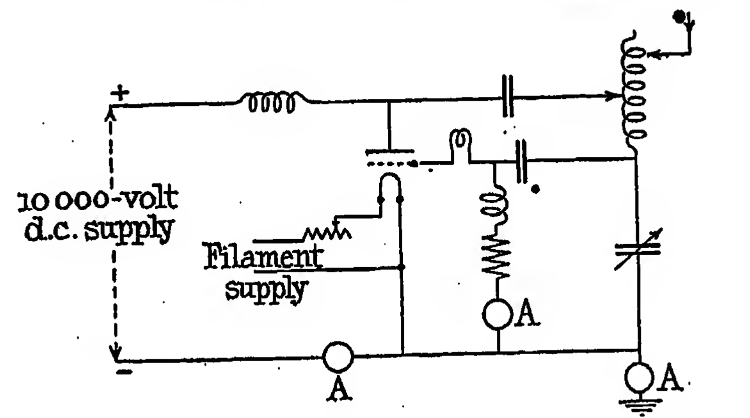

FIG. 1.

mental, as no set of this power had previously been attempted by the Post Office. Having in view the design of future high-power stations, the equipment was retained for experimental investigations.

The circuit is a modification of Colpitt's arrangement and is shown in skeleton in Fig. 1. Since the filaments of both rectifying and transmitting valves are fed from the three-phase supply, the only running machines necessary are the air compressor for the Creed key and the air blower for cooling the valve seals.

Two types of transmitting valve have been tried, namely, the Mullard silica valve and the Western Electric Co.'s water-cooled metal valve. The relative capacities of these are tabulated below.

Valve	Dissipation	Full-load output	Maximum anode voltage	Filament consumption
	kW	kW	volts	watts
Silica ..	2·5	7	10 000	720
Water-cooled	10	10	10 000	900

Installation of a coupled circuit for the arc sets.—A coupled circuit was designed and installed within a few

weeks of the station being put into commission. This had the effect of practically eliminating harmonic radiation, but under certain conditions the circuit became unstable.

The frequency of the oscillations generated is determined by the resonant frequency of the circuit shunted across the arc. If a secondary circuit is coupled to the

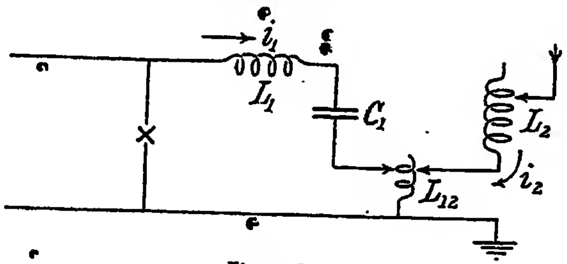

FIG. 2.

primary circuit (Fig. 2) it will be equivalent to an impedance Z_1' in the primary circuit, where

$$Z_1' = (i_2^2/i_1^2)(R_2 - jX_2) = (R_2 - jX_2)\ (\omega^2 L_{12}^2/Z_2^2),$$

X_2 being the reactance of the secondary circuit and L_{12} the mutual inductance between the two circuits. Thus the frequency generated will be a function of the coupling, the secondary resistance and the mistuning of the two

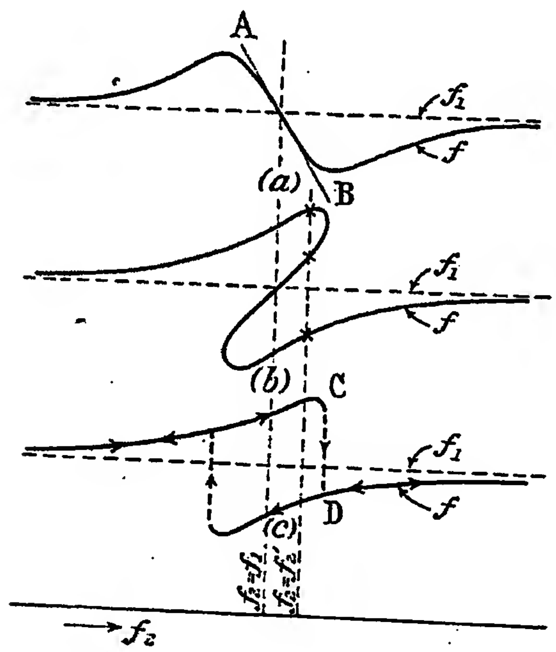

FIG. 3.

f = generated frequency.
f_1 = resonant frequency of primary circuit.
f_2 = resonant frequency of secondary circuit.

circuits. The actual equation for the frequency is a cubic and is given by

$$X_1 - \frac{\omega^2 L_{12}^2}{Z_2^2} X_2 = 0$$

where X_1 = the reactance of the primary circuit at the generated frequency.

The above equation may have either one or three real roots, depending upon the value of the mutual inductance between the two circuits. A typical frequency curve is indicated in Fig. 3 (*a*) in which the frequency generated (f) is plotted against the natural frequency of the secondary circuit (f_2). As the coupling is increased the slope of the line AB increases up to, and then beyond, 90°. In the latter case there may be three frequencies corresponding to any one tune f_2' of the secondary circuit [see Fig. 3 (*b*)]. If such a curve is plotted from practical measurements it becomes discontinuous as in Fig. 3 (*c*), i.e. it is possible that for one condition of tuning between primary and secondary circuits either one of two frequencies may be generated, depending upon the previous tuning conditions. Associated with the sudden frequency change at CD is a current and current-ratio change as indicated in Fig. 4, in which the ratio between secondary and primary currents (i_2/i_1) is plotted against the natural frequency f_2 of the secondary circuit.

Möller * in his paper on "The Theory of Ziehen," discusses the theory of the coupled circuit and gives formulæ and graphical methods for determining the frequency generated, the ratio between primary and secondary current, etc. The coupling which corresponds to a slope of AB equal to 90° [Fig. 3 (*a*)] is defined by Möller as the critical coupling. Beyond this coupling the change in frequency takes place not at resonance, but is drawn out beyond resonance between primary

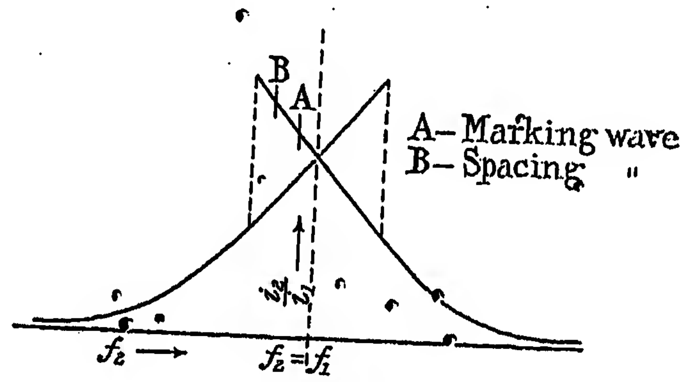

FIG. 4.

and secondary circuits as in Fig. 3 (*c*). This drawing out of the curve has been given the name of "ziehen" by Möller.

Obviously the above conditions either below or above the critical coupling may become unstable. In practice, however, it is found desirable to work with a fairly tight coupling corresponding to several times the critical coupling. Further, the limiting position of "ziehen" is definite and the set may be operated safely with the secondary circuit tuned beyond resonance, i.e. in the region of "ziehen" as indicated in Fig. 4, which shows the approximate working conditions for marking and spacing waves. The advantages derived from working within this region are improved efficiency and steadiness of working.

Tests on insulating materials.—Insulating materials for radio-frequency work must have low dielectric hysteresis losses, and these, rather than leakage losses, often determine the choice of insulating material. The usual form of test consists in placing samples of different materials of the same dimensions between two electrodes across which a pressure up to 30 000–40 000 volts at a frequency of 40 000–60 000 periods per second is applied. Observations are then taken of the breakdown voltage or temperature-rise.

Samples of wood 1 in. square × 4 in. long were tested,

* *Jahrbuch der drahtlosen Telegraphie und Telephonie*, 1920, vol. 16, p. 402.

the voltage being applied between the ends. Many kinds of wood break down and burn at voltages below 20 000, but American whitewood has been repeatedly tested and, after a short run during which the residual moisture is driven from the wood, has remained cool even when a voltage of 30 000–40 000 is applied for an indefinite period, and one sample tested to 55 000 volts showed no signs of serious heating or breakdown. The usual form of breakdown consists in a charring of the wood at points, not necessarily in contact with the electrodes. This gradually spreads along the grain, linking up and finally causing a flash-over. Comparative tests between whitewood, paxolin, bakelite and ebonite showed that whitewood was superior to paxolin and bakelite and compared favourably with ebonite.

In addition, numerous tests have been made on various kinds of granite, porcelain, etc., in connection with the Rugby Radio Station.

PROCEEDINGS OF THE INSTITUTION.

717TH ORDINARY MEETING, 24 APRIL, 1924.

(Held in the Institution Lecture Theatre.)

Dr. A. Russell, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting of the 10th April, 1924, were taken as read and were confirmed and signed.

The President: Before presenting the Faraday Medal to Dr. S. Z. de Ferranti, I shall call upon Colonel Crompton and Mr. Partridge to say a few words.

Colonel R. E. B. Crompton: In the very early days we electrical beginners found that the best way of advertising the dynamos and arc lights that we were then making, was by travelling the country with portable sets of arc lighting apparatus, so that we were looked upon rather as scientific showmen than as engineers. We were paid for lighting the grounds of the Alexandra Palace, and Sydney Baynes, who is now the Borough Electrical Engineer at St. Pancras, was in charge of the apparatus. He told me that a young man had become very interested in the working of our plant: that young man was Ferranti. A year or two later I met Ferranti again at the time when we were both hard at work trying to persuade the English public that the electric light was far superior to gas as it had no objectionable smell. We both found at that time that the hardest part of our work was to induce a few leading men who had brains, and at the same time sufficient money, to invest a little of the latter in our respective first attempts at supplying electric light from central stations. In carrying out this work Ferranti and I started on distinct and separate lines. He faced all the troubles, and invented all the distributing gear to enable the alternating current to be transmitted over a distance and converted at the users' premises, so as to allow the use of the 100-volt Swan lamps that were then available. I, on my part, put down smaller stations and supplied direct current at lower pressures, using accumulators. We both had our problems, but we both found that the biggest problem of all was finance. I had one advantage over Ferranti. He had to deal with the whole question of designing the power plant that he employed, whereas I shared the problem of the steam plant with that great genius P. W. Willans, so that in my case half the difficult problems were worked out for me by Willans. Ferranti was the first man to conceive the idea of a capital station placed in the most advantageous position to obtain cheap fuel supply and ample condensing water, and from thence to transmit at high pressure to interurban converting stations. He, therefore, is the real inventor of the capital power station. I think that Ferranti now sees that both of us played our part, at any rate that the early stage at which I with my smaller stations was able to generate and distribute at such a cost that we could pay dividends, eventually greatly helped his ideas. I need hardly say more; Ferranti as a steam engineer, as a designer of generating machinery, of high-pressure cables and of the distributing devices necessary with alternating current, was the man who did more than anyone else to start the electrical engineering profession, and no one knows it better than I.

Mr. G. W. Partridge: There is an old saying, "Honour to whom honour is due," and I have always thought that Ferranti never had the proper recognition which he should have had for the stupendous work he carried out 30 to 35 years ago. No one knows better than I the difficulties with which he had to contend and the marvellous way in which he overcame them. It was said by many in those days that Ferranti was 20 years in advance of his time, and that no good would come of his invention; but if we compare Ferranti's work 30 years ago with the most modern and up-to-date practice to-day we must all be proud that he belongs to this country. I think it may be of interest if I touch on one or two things which Ferranti did in those very early days. In 1886 he first conceived the idea, and saw the advantage, of running transformers in parallel, thereby making the alternating-current system

self-regulating. In those days when the system of generation and transmission was at 100 volts, or at the most 200 volts, and when small stations were supplying small areas in different parts of the cities and towns of this country, Ferranti conceived the idea of the capital station—the large station outside the inhabited area, on the river with ample water for condensing purposes, and room for extensions and with no risk of receiving an injunction for nuisance. In doing this it became necessary for him to increase the pressure, and he increased it to 10 000 volts, or 50 to 100 times as high as any other pressure then in use. In order to carry this into effect it became necessary for him to design every detail practically from the engine up to the meters controlling the lamps. In those days there were no alternating-current meters and we sold the current at so much a lamp per annum. Ferranti designed his generators—generators 10 times as large as any others then in use in this country, and generating direct at 10 000 volts, which to-day is about the maximum pressure for generators. Ferranti had to design every single detail himself, and in nearly every case he had actually to make it himself. Having got his generating station to work, he found that the cables which had been supplied by an outside contractor were quite inadequate to run at such a high pressure and broke down continuously. Most engineers would have been in despair, but Ferranti immediately set to work to design his own paper-insulated cables, 14 miles of which are still in use running at a pressure of 11 000 volts. What do we find to-day? In the most up-to-date practice all cables, whether used for high or low pressure, are paper-insulated—exactly the same insulation as Ferranti used in those early days. A well-known engineer recently remarked to me, "Well, Ferranti must be a very old man now." Does he look an old man? I told this engineer Ferranti's age and he was dumbfounded that any one man at the age of 20 or thereabouts should have conceived and carried out such stupendous work. It is a great pity that the British electrical industry did not take advantage of Ferranti's genius and so get a start of all other countries, but this was entirely due to Government legislation. If there had been a medal for valour in those days similar to the much-coveted Victoria Cross, Ferranti would surely have been given it for his courage and perseverance in the face of enormous difficulties. There is, however, a medal given by the Institution which confers the highest possible honour it can give, and everyone will agree that in presenting the Faraday Medal to Dr. Ferranti it is being given to one who is in every way worthy of it.

The President: In his Presidential Address* to the Institution in 1910, Dr. Ferranti advocated electricity everywhere and for all purposes. During the 36 years since I first met him, I know of no one who has striven harder or more successfully to advance the applications of electrical science. This is exactly the object for which this Institution was founded. It is natural, therefore, that we should all delight to honour Dr. Ferranti.

The President then presented, in the name of the Institution, the Faraday Medal to Dr. Ferranti.

* *Journal I.E.E.*, 1911, vol. 46, p. 6.

Dr. S. Z. de Ferranti: I cannot express how deeply I feel the honour which has been conferred upon me by the Institution. Going back to those very early days about which Colonel Crompton has spoken, I have always appreciated, and have never forgotten, the very great effect which the obtaining of knowledge from those who were actually engaged in the production of electric light had upon me. Colonel Crompton and his assistants freely showed me all that they were doing and gave me all the information they could, so that I had the first chance of acquiring that knowledge which was so necessary to me afterwards. Later on I derived the greatest possible help from being allowed as a boy to work with Mr. Sydney Baynes, Colonel Crompton's chief assistant in the installation of the electric light at King's Cross terminus. As the President has mentioned, I have for a very long time striven to increase the applications of electricity. I take this Medal as a compensation for my failures and as an encouragement for further work in this same good cause. I wish to remind you all, as I endeavoured to do in my Presidential Address to the Institution in 1910, that we cannot have too much electricity. In that Address I attempted to show what should be done and the course that should be followed. I feel that although electricity has gone very far and its application is enormous, the progress since 1910 is somewhat disappointing. I think that this is largely due to the fact that there has been no fundamental reduction in the cost of generating electricity. Electricity supply has become a very complicated business, and I feel that in the future the process must be greatly simplified. I wish to remind members of this Institution, and electrical engineers generally, that the electrical engineer's work along this one line alone will only be approaching completion when there is no more combustion carried on for either power or heat within populous areas. I am more than ever persuaded that eventually we shall use electricity for all the services which are now served through the burning of some kind of fuel within such areas. Electricity, even to-day, is the great labour-saver. Electricity under those conditions would be an immensely greater labour-saver and I feel that discoveries will be made which will enable us to generate electricity much more cheaply and so bring in its train the other simplifications connected with electrical supply and make such a system that electricity can be furnished for all our wants, as I have just explained. Even though I feel that I, myself, can only accomplish very little, I shall hope so to encourage others and excite their interest that they will work on this subject and eventually bring it to success. In conclusion, I should again like to say how much I appreciate the honour which has been conferred upon me by the presentation of this Medal. I appreciate it now, and for the rest of my life I shall continue to appreciate it just as much.

Mr. G. Semenza then delivered the Fifteenth Kelvin Lecture entitled "Kelvin and the Economics of the Generation and Distribution of Electrical Energy" (see page 882). A vote of thanks to the lecturer, proposed by Mr. W. M. Mordey and seconded by Mr. R. T. Smith, was carried with acclamation, and the meeting terminated at 7.53 p.m.

39th MEETING OF THE WIRELESS SECTION, 7 MAY, 1924.

(Held in the Institution Lecture Theatre.)

Mr. E. H. Shaughnessy, O.B.E., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 2nd April, 1924, were taken as read and were confirmed and signed.

A paper by Mr. L. C. Pocock, B.Sc., Associate Member, entitled "Faithful Reproduction in Radio-Telephony" (see page 791), was read and discussed.

On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 8 p.m.

52nd ANNUAL GENERAL MEETING, 8 MAY, 1924.

(Held in The Institution Lecture Theatre.)

Sir James Devonshire, K.B.E., Vice-President, took the chair at 6 p.m.

The Chairman: The President is representing the Institution to-night at the Annual Dinner of the Iron and Steel Institute and he has asked me to preside at this meeting in his absence.

The notice convening the meeting was taken as read. The minutes of the Ordinary Meeting held on the 24th April, 1924, were also taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

Messrs. A. W. Marshall and R. W. Hughman were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows:—

Elections.

Members.

McNicol, Archibald John.
Turner, Edgar Perceval.

Associate Members.

Armstrong, Reginald Basil.
Ash, Arthur Stanley.
Baxter, James MacGowan.
Canning, Sidney, B.Sc. (Eng.).
Chiba, Shigetaro.
Clerk, George Brownlow.
Connor, Robert.
Drape, Stanley.
Dymond, John Drayson.
Green, Alexander Henderson.
Hargreaves, Tom.
Jones, Reginald Cleveland.
Kitchen, Percy Inman.
Leslie, George Herbert, Captain, A.E.C.
Lloyd, Thomas.
Mazoomdar, Tarak Charan.
Pantvaidya, Mahadev Vaman.
Rann, John Selwyn.
Raworth, Alfred.
Webber, Ernest Clifford.
Wigner, Sydney Howard.

Graduates.

Banks, Albert.
Boddington, Frank Stanfield.
Bradley, Robert Walter.
Chase, Stephen Hayter.
Downie, Christopher Edmund.
Galbraith, Reginald Arthur H., Lieut., R.C.C.S.
Gardner, Geoffrey Harold.
Gupta, Krishna Chandra.
Halle, Charles Richard.
Hobbs, Percy George.
Holt, Walter Raymond K.
Hudson, William James.
Leake, William Richard.
L'Estrange, Wilton Oldham.

Graduates—continued.

Narasimham, R. D., B.E., M.E.
Nunn, Darrell.
O'Sullivan, Stephen.
Philip, Archibald, B.Sc.
Pocock, Hugh Shellshear.
Stobbs, John George.
Taylor, Harold Charles.
Todd, William Montgomery.
Tuffill, George William.
Williams, Thomas Vaughan.

Students.

Aschman, Geoffrey Donald.
Atkinson, Sidney.
Baldwin, Alfred William T.
Barker, Frederick Albert.
Barratt, Noel Marshall.
Bennett, James Miller.
Blizard, Charles Hillyer.
Boardman, Tom.
Boullen, Harold Godfrey.
Campbell, Michael C.
Carruthers, John Edward.
Dowe, Henry George P.
Durand, Philippe Henri R.
Edwards, Sydney Lawrence.
Elven, Robert Slade.
Farnes, Thomas Louis.
Farnworth, Benjamin.
Field, Arthur Henry M.
Fryer, Harold Herbert.
Gardiner, Robert Charles.
Gibson, Thomas.
Green, George Norman.
Higson, Donald Hesketh.
Holt, Philip John.
Hubbard, Edward John E., B.A.
Jones, Arnold Edward.
Landsbert, Reginald Ernest.
Lucette, Philip Arthur C.
MacColl, Hugh Geoffrey.
Mainar, Oswald Edwin.
McWhirter, Eric Malcolm S.
Middleton, Samuel Charles.
Mitchell, Denys Lindley.
Moffatt, Joseph Walton.
Newton, John Alfred.
Odling-Smee, Charles William.
Orchard, Frederick Charles.
Parry, Herbert Watkin T.
Perris, Frank Robert, B.Sc.
Pheasant, John William A.
Pollock, Jack Campbell.
Porter, Frank.
Potter, Jack.
Prangnell, James Ernest.
Rice, Edmund Stewart, Jun.
Roberts, David Harold.
Roberts, Frederick Walter.
Roberts, Leonard Craig.
Robertson, Philip White.
Sakr, Hussein Tewfik.
Shaw, Thomas Frederick.
Shields, Ernest Gerald.
Showler, Thomas Henry.
Smith, Cyril Blake.
Tagg, George Frank.
Turnbull, Frederick Laughlin.
Vaughan, Alfred Bentley.
Walter, Charles Lockhart.
Warrington, Eric.
Webb, Frederick George.
Wharfe, Lawrence Edward.
Whitcher, Athol Eric J.
Willard, Leslie Albert.
Williams, Harold.
Williams, James Rex.

TRANSFERS.

Associate Member to Member.

Cave-Brown-Cave, Nigel Frederick, Capt., B.Sc.
Clayton, Albert Edmund, D.Sc.
Dawson, Boyd.
Hilder, Walter Trevethan.
McKinnon, Ernest Cyril.
Myers, Ernest Robertson.
Regnauld, Alfred, B.Sc.
Sharp, Harry Gilkes.
Sims, John Walter.
Wilkinson, Arthur Rowland.

Graduate to Associate Member.

Anderson, John.
Dennis, William Edwin.
Dunbar, Leslie.
MacEwan, Lewis Barclay, B.Sc.
Nixon, Thomas Edgar B.

Student to Associate Member.

Esmond, Leslie Purcell.
Ferguson, Alexander Dalgety.
Heritage, Hubert James E.
Jolly, Edward Ernest.
Lyon, Edwin.
Steel, Harry Gordon.
Topley, Harry.

Associate to Associate Member.

Sloan, George Andrew.

Student to Graduate.

Burgum, William Thomas.
Deedes, John Gordon, M.B.E., Capt., R.C.S.
Gerry, Lionel Frederick.
Latham, Ashton.
McLennan, Roderick Arthur.
Millington, Stanley.
Ogilvie, Harold Erskine.
Verity, Conrad Edward H.
Wellsteed, Albert Edward.
Wright, George Thomas.

Messrs. R. Grierson, F. Pooley and Captain R. J. Wallis-Jones were appointed scrutineers of the ballot for the election of new Members of Council.

The following lists of donations were taken as read and the thanks of the meeting were accorded to the donors.

Library.—Messrs. George Allen and Unwin, Ltd.; R. M. Archer; the Astronomer Royal; Messrs. E. Benn, Ltd.; C. Boileau; the British Cast Iron Research Association; the British Engineering Standards Association; J. Bruce; Department of the Interior, Canada; Messrs. Chapman & Hall, Ltd.; the Chief Experimental Officer, Signals Experimental Establishment, Woolwich; the Chief Inspector of Factories; Dr. A. E. Clayton; C. G. Conradi; Messrs. Constable and Co., Ltd.; W. R. Cooper; the Director-General of Posts and Telegraphs, India; Dr. C. V. Drysdale, O.B.E.; C. F. Elwell; Dr. J. A. Fleming, F.R.S.; B. Hague; K. Hedges; F. L. Henley; the Imperial Mineral Resources Bureau; the Institution of Heating and Ventilating Engineers (Incorp.); the Institution of Royal Engineers, Chatham; the International Electrotechnical Commission; A. C. Jolley; Dr. A. E. Kennelly; E. T. Larner; Prof. M. Maclean; Prof. E. W. Marchant; Messrs. Marconi International Code Co., Ltd.; J. W. Meares, C.I.E.; the Meteorological Office; Prof. S. Narayan; the National Electric Lamp Association, Ohio; R. E. Neale; E. W. L. Nicol; Messrs. Sir Isaac Pitman and Sons, Ltd.; Purdue University; J. H. Reyner; Dr. A. Russell, F.R.S.; Dr. E. Sacchetto; M. G. Say; H. G. Solomon; Dr. S. P. Smith; Messrs. E. and F. N. Spon, Ltd.; S. G. Starling; C. F. Wade; Prof. Miles Walker; and Messrs. Williams and Norgate.

Benevolent Fund (see list of Donations on page 480).

The Chairman, after reviewing the work of the session, moved "That the Annual Report of the Council * for the year 1923-24, as presented, be received and adopted."

The resolution was seconded by **Prof. E. W. Marchant, D.Sc.,** and comments and suggestions were made by **Mr. W. R. Cooper, Mr. J. J. Stewart** and **Mr. F. W. Purse,** to which the Chairman replied as follows:—

The Chairman: Mr. Cooper may be assured that the improvement of the lighting of the Lecture Theatre is very much in hand. I can assure Mr. Stewart, who spoke in regard to the Electrical Appointments Board, that the sense of his remarks will be transmitted to the proper Committee. We are much obliged to Mr. Purse for taking notice of the work of the Council in obtaining the privilege for the members to use the title "Chartered Electrical Engineer."

The Report was then unanimously adopted.

Mr. P. D. Tuckett (Hon. Treasurer): It is your misfortune that the Bye-Laws have deprived you of so exceptionally capable an Honorary Treasurer as you possessed in Sir James Devonshire, but I am glad to say that the inherent vitality of the Institution enables me to submit a Statement of Accounts with which I think the members have every reason to feel satisfied. The year's Income shows an increase of £596, and the Expenditure a reduction of £5 020, omitting the various Reserve provisions at the foot of the Accounts. The increased Income is mainly due to an increase of £1 000 in subscriptions, offset to the extent of £394 by reduced Entrance Fees and to the extent of £141 by reduced Dividends and Interest. The reduced Expenditure is spread over a number of items. First, there is the elimination of the following special items which appeared in last year's Accounts, viz. H.M. Office of Works, £222; Commemoration Meetings, £226; War Memorial, £85; Faraday Medal, £113; Thompson Memorial Library, £32; and there is also a reduction of £285 in the expenses incidental to the Royal Charter. Next, there are gratifying reductions of £525 in Management Expenses, of £387 in the various items under the heading "Institution Building," of £335 in Mortgage Interest, of £433 in the net cost of the *Journal*, of £28 in the cost of the Institution Meetings, and of £325 in the cost of the Local Centres; and, lastly, there is the large reduction of £1 057 in the net cost of *Science Abstracts*, and a further reduction of £900 odd in the net annual cost of this building, resulting from an increase of that amount in the rents paid by our tenants and deducted from the gross cost. Last year these rents amounted to £3 474, as compared with £2 491 in the previous year. For the current year, now that the building is fully let, they will exceed £5 500, so that the portion of the building reserved for Institution purposes is enjoyed by us at a very moderate cost. The reduction in the net cost of the *Journal* is due to an increase of £1 413 from Sales

* See page 526.

and Advertisements, and a similar increase of £1 360 accounts for the reduced cost of *Science Abstracts*. In 1921 *Science Abstracts* cost us £978, and in 1922 £1 084, whereas this last year we were called upon to find only £27. I think that the Committee controlling the publication are to be congratulated on this very marked improvement, which I hope we shall see maintained in the current year. Referring to what I have called the Reserve provisions at the foot of the Revenue Account, it will be seen that £4 500 has been applied to redeeming the balance of the mortgage on the Tothill-street property, as compared with £3 000 applied to its reduction in the previous year, while £1 701 has been spent on Furniture, Fittings and Apparatus, as compared with £718. There is no very material difference in the other items, but it will be noted with satisfaction that the Balance carried to the General Fund in the Balance Sheet is £3 957, as compared with £862 a year ago. For the current year there will be a decrease of some £3 500 in the income from subscriptions, consequent on the reductions which were sanctioned a year ago and which came into force at the beginning of this year, but I hope that this decrease may be largely made good by additional membership, by the increased rents now being paid by our tenants, by increased sales of the *Journal* and advertising receipts, and by the return on the accumulated surplus of last year. Turning to the Balance Sheet, it will be seen, as mentioned in the Report, that taking the Tothill-street property and the Investments at cost, and the Institution Building, the Library and the Furniture at their written-down values, the Assets amount to £145 239; and deducting from this figure the outstanding mortgage of £14 801 on this building, and the other liabilities aggregating £5 038, there is a net surplus of £125 399, showing an increase of £11 000 over the corresponding figure a year ago. This gratifying result affords striking evidence of our strong financial position and, if the progress of the industry is what I believe we have every reason to anticipate it will be, should ensure our ability to take advantage of the enlarged scope for our many activities. The various items in the Accounts have been dealt with on the same lines as before and appear to me to call for no special comment, and I do not propose therefore to take up time by reviewing the detailed figures, but I shall of course be glad to furnish any explanation of them which any member may desire. As indicated in the Note at the foot of the Accounts, the Investments are taken at cost and show some depreciation, but I am glad to say that it now amounts to less than £1 000, so that those members who are optimistically inclined may justifiably hope before very long to see the Investments worth the figure at which they stand. That is all which I have to say on the Accounts, but I should like to take this opportunity of expressing my grateful appreciation of the extremely careful and businesslike way in which they are kept by the Secretary and his staff. I now formally move: "That the Statement of Accounts and Balance Sheet for the year ended 31st December, 1923,* as presented, be received and adopted."

The resolution was seconded by **Mr. F. Pooley** and, after **the Chairman** had replied to comments by **Mr. F. W. Purse,** was unanimously adopted.

The following resolution, moved by **Mr. W. R. Rawlings** and seconded by **Mr. A. H. Allen,** was carried with acclamation: "That the best thanks of the Institution be accorded to the following officers for their valuable services during the past year: (*a*) The Hon. Secretaries of the Local Centres and the Local Hon. Secretaries and Treasurers abroad: (*b*) The Hon. Treasurer (Mr. P. D. Tuckett)."

Captain R. J. Wallis-Jones then moved "That Messrs. Allen, Attfield & Co. be appointed Auditors for the year 1924–25."

The resolution was seconded by **Mr. W. E. Rogers** and carried unanimously.

The meeting terminated at 6.40 p.m.

* See page 536.

INSTITUTION NOTES.

Scholarships.

The following Scholarships have been awarded by the Council for 1924–25 :—

David Hughes Scholarship (*value* £50).

H. E. W. Tumath (Belfast Municipal College of Technology).

Salomons Scholarship (*value* £50).

E. Youel (Liverpool University).

Associate Membership.

Candidates for Associate Membership are reminded that they may present a thesis in lieu of taking the A.M.I.E.E. Examination. Members are asked to bring this fact to the notice of anyone intending to apply for admission to that class.

Third International Conference on E.H.T. Supply Systems.

The Council have decided that the Institution shall be represented at the above Conference, to be held at Paris next June (see page 816), and the following British National Committee has been set up to co-operate with the French Committee, to co-ordinate the work of the British representatives, to watch British interests, and to arrange for the submission of reports to the Conference. The British Dominions are to be invited, through the Institution's Local Honorary Secretaries, to nominate representatives to attend the Conference.

BRITISH COMMITTEE.

W. B. Woodhouse (*Chairman*).

J. R. Beard
T. Bolton
N. E. P. Harris
A. Jacob
R. Borlase Matthews
E. Parry
G. V. Twiss

The Chairman of the Papers Committee, and representatives of the following :—

The Electricity Commissioners.
The British Electrical and Allied Manufacturers' Association.
The Cable Makers' Association.
The British Engineering Standards Association.
The British Electrical and Allied Industries Research Association.
The General Post Office.
The Incorporated Municipal Electrical Association.
The International Electrotechnical Commission.
The Incorporated Association of Electric Power Companies.

The Benevolent Fund.

The following is a list of the Donations and Annual Subscriptions received during the period 26 September–25 October, 1924 :—

	£	s.	d.
Bloome, J. (Manchester)		2	6
Farrer, M. (Twickenham)		5	0
French, A. J. (London)		10	6*
Gibbins, J. (Newcastle-on-Tyne)		2	6
Gilbert Club (per Mr. C. E. Benham)	40	5	11
Lisle, G. S. (Gateshead-on-Tyne)		5	0
Smith, A. Eric (Tipton)	1	1	0
Smith, J. L. (Leyton)		5	0
Verity, G. (Birmingham)	1	1	0
Walter, C. L. (Christchurch, N.Z.)		5	0

* Annual Subscription.

The following have subscribed £5 or more in one amount to the Benevolent Fund since its inception in 1890 :—

	Total Subscribed to 25th Oct., 1924. £	s.	d.
Abel, Sir Frederick, Bart., F.R.S.	5	5	0
Anderson, Sir James	26	5	0
Andrews, W.	52	10	0
Aron, Professor H.	5	5	0
Aron Electricity Meter, Ltd.	10	10	0
Associated Municipal Electrical Engineers (Greater London Centre)	7	7	0
Atkinson, Ll. B.	44	19	0
Ayrton, Prof. W. E., F.R.S.	5	5	0
Babcock and Wilcox, Ltd.	26	5	0
Bailie, J. D.	5	5	0
Barnes, A. S.	7	10	0
Bazley, Sir Thomas, Bart.	10	10	0
Bell, Major Herbert, O.B.E.	5	5	0
Bennett, A. R.	5	5	0
Binyon, B., O.B.E.	5	0	0
Bowden, H. W.	5	5	0
British Insulated Wire Co., Ltd.	26	5	0
British Thomson-Houston Co., Ltd.	26	5	0
British Westinghouse Co., Ltd.	52	10	0
Broomfield, F. H.	5	5	0
Brydon, S.	5	0	0
Buckingham, A. O.	10	10	0
"Building Trades' Gift to the Nation"	57	9	6
Burnand, W. E.	28	7	0
Byng, G.	243	1	0
Byng, M.	19	19	0
Cappel, Sir Albert J. Leppoc, K.C.I.E.	10	0	0
Cater, J. McI.	10	10	0
Chamen, W. A.	11	11	0
China Furniture and Electrical Fittings Manufacturers' Association	26	5	0
Chloride Electrical Storage Co., Ltd.	10	10	0
Clark, Latimer, F.R.S.	5	5	0

	Total Subscribed to 25th Oct., 1924. £	s.	d.
Clay, C. B.	11	6	0
Clements, F. W.	25	0	0
Collins, W.	8	8	0
Committee for Protection of Electrical Interests	24	9	0
Cooper, W. R.	5	5	0
Cornish, V. K.	16	16	6
Cox, C. W.	5	0	0
Crompton, Col. R. E. B., C.B.	11	11	0
Crookes, Sir William, O.M., F.R.S.	5	5	0
Cross, A. S.	6	1	0
Dallas, J. D.	60	0	0
Davies, B.	27	17	6
Davis and Timmins, Ltd.	10	10	0
Deacon, M.	5	5	0
Dearlove, J. A. L.	50	0	0
Devonshire, Sir James, K.B.E.	23	2	0
Dick, Kerr and Co., Ltd.	26	5	0
Disabled Soldiers and Sailors Training Fund, Guarantors of the	23	18	4
Donovan, H. C.	121	5	0
Douglass, Sir James	10	10	0
Dugard Brothers	5	0	0
Dykes, A. H.	8	3	0
Eccles, Dr. W. H., F.R.S.	55	0	0
Edgcumbe, K.	49	8	0
Edmunds, H.	10	0	0
Electrical Power Storage Co., Ltd.	26	5	0
Electrical Engineers' Ball Committee	606	11	4
Electrical Review, Ltd.	5	5	0
Electrical Standardizing, Testing and Training Institution, Ltd.	50	0	0
Electrician Printing and Publishing Co.	5	5	0
Ellis, A.	5	5	0
Ellis, H. S.	6	6	0
Elwell, C. F.	5	17	0
Esson, W. B.	105	0	0
Evershed, S.	83	12	0
Evershed and Vignoles, Ltd.	5	5	0
Ferguson Pailin, Ltd.	10	0	0
Festing, Edward Robert, Major-General, R.E., C.B., F.R.S.	10	0	0
Fisher, F. L.	5	5	0
Fletcher, R. H., B.A.	10	3	6
Forbes, Prof. G., F.R.S.	50	0	0
Fortescue, Prof. C. L.	11	5	0
Foster, Prof. George Carey, LL.D., D.Sc., F.R.S.	5	5	0
Foster Engineering Co., Ltd.	5	5	0
Fowler and Lancaster	5	0	0
Franklin, C. S.	10	0	0
Garcke, E.	297	5	0
Gavey, Sir John, C.B.	18	7	0
General Electric Co., Ltd.	62	0	0
Gilbert Club	40	5	11
Gilbert Tercentenary Fund	6	1	11
Gladstone, Dr. J. H.	10	0	0
Glasgow (City of) Royal Engineer Volunteers	197	0	11
Gobie, H.	9	17	0
Gorham, J. M.	5	5	0
Goslin, E. T.	11	1	0
Graham, A., and Mullard, Capt. S. R.	15	0	0
Graham, W. J.	5	0	0
Gray, J. Hunter, K.C.	16	5	0
Gray, R. K.	258	8	0
"R. K. Gray Portrait Fund"	8	11	9
Grime, R. E.	5	0	0
Hammond, R.	19	19	0
Harrison, H. E.	11	11	0
Harvey, T. H. M.	12	12	0
Hawtayne, W. C. C.	14	14	0
Heaphy, M.	10	10	0
Hedges, K.	32	3	0
Henderson, Sir James	5	0	0
Henley's Telegraph Works Co., Ltd.	280	0	0
Highfield, J. S.	36	10	0
Hirst, H.	64	11	6
Hockley, N. J.	7	2	0
Hooper's Telegraph and India Rubber Works, Ltd.	5	5	0
Howe, Prof. G. W. O., D.Sc.	10	0	0
Hughes, Prof. D. E., F.R.S.	5	5	0
Hughman, Sir E. M.	250	0	0
Hunter, P. V., C.B.E.	7	7	0
Incorporated Municipal Electrical Association	102	10	0
Ingleby, J. C. B.	10	0	0
Institution of Railway Signal Engineers	31	10	0
Jackson, Admiral Sir H. B., R.N., G.C.B., K.C.V.O., F.R.S.	17	4	0
Jackson, Col. R. R.	20	10	0
Jewell, C. J.	7	12	6
Johnson Matthey and Co., Ltd.	10	10	0
Jonas and Colver, Ltd.	5	5	0
Jones, A. Ernest	5	5	0
Jones, Charles Edward	6	11	0
Kapp, Dr. G.	19	19	0
Kelvin, The Rt. Hon. Lord, O.M., G.C.V.O., F.R.S.	27	6	0
Kemnal, Sir James	6	6	0
Kennedy, Sir Alexander, F.R.S.	50	0	0
Kennedy and Donkin	10	10	0
Kensit, H. E. M.	11	6	6
Kerr, W. T.	17	7	0
Kolle, H. W.	50	8	0
Lacey, E. M.	25	0	0
Leach, H. L.	17	7	0
Lord, F. A. B.	5	5	0
Mackenzie, T. B.	7	1	0
MacWhirter, A. C.	7	7	0
Makower, A. J.	5	15	0
Mance, Sir Henry, C.I.E.	27	5	0
Marchant, Prof. E. W., D.Sc.	10	17	0
Marconi's Wireless Telegraph Co., Ltd.	50	0	0
Marryat, H.	6	1	0
Marsh, F. R.	40	10	0
Mather, Prof. T., F.R.S.	17	2	0
Mavor and Coulson, Ltd.	10	0	0
Maxwell, J. M. Scott	9	8	6
Medhurst, F. H.	5	5	0
Merz, C. H.	48	6	0
Midland Electrical Engineers' Ball Committee	91	0	0

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Mordey, W. M.	57	17	6
Morse, S.	10	0	0
Mullard, Capt. S. R.	6	1	0
Mullard, Capt. S. R. and Graham, A.	15	0	0
Nalder, F. H.	6	0	0
Nalder Brothers and Thompson, Ltd.	5	5	0
Nash, G. H.	10	0	0
Newman, A. J.	15	10	0
Nisbett, G. H.	10	0	0
Noble, Sir William	6	6	0
Northey, P. W.	10	10	0
Oerlikon Maschinenfabrik	5	0	0
Olympia Electrical Exhibition	553	17	7
Osram Lamp Works	52	10	0
Paris, E. A.	10	0	0
Parsons, Hon. Sir Charles, K.C.B., F.R.S.	120	0	0
Patchell, W. H.	47	4	0
Pell, Bennett	5	5	0
Perry, Prof. J., LL.D., D.Sc., F.R.S.	5	5	0
Phillips, S. E.	10	0	0
Pilkington, D. F.	6	0	0
Pirelli, Ltd.	10	0	0
Pletts, J. St. V.	5	0	0
Preece, Sir William, K.C.B., F.R.S.	24	2	0
Probert, I.	5	5	0
Pyne, A. P.	8	8	0
Raphael, F. C.	10	10	0
Renwick, Sir Harry, K.B.E.	5	5	0
Rider, J. H.	105	0	0
Roberts, D. E.	12	12	0
Robertson Electric Lamps, Ltd.	21	0	0
Robinson, Mark	44	0	0
Rogers, H. I., O.B.E.	6	18	6
Rosling, P.	26	5	0
Round, Capt. H. J., M.C.	5	5	0
Royal Engineer Volunteers	31	9	6
Rücker, Sir A. W.	5	5	0
Russell, Dr. A., M.A., LL.D., F.R.S.	15	15	0
Russell, The Rt. Hon. the Earl	5	0	0
Salomons, Sir David, Bart.	176	5	0
Sanders, T.	5	5	0
Sayers, J. E.	14	4	0
Scott, W. A.	10	10	0
Scott, W. H., O.B.E.	36	15	0
Selvey, W. M.	7	19	6
Sharp, S.	17	17	0
Siemens, A.	90	6	0
Sillar, A. M.	5	5	0
Sillar, K. G.	5	0	0
Sinclair, D.	6	1	0
Sloan Electrical Co., Ltd.	5	5	0
Smith, T. V., Major, M.C., R.A.F.	5	5	0
Smith, W. O.	10	10	0
Smith, Willoughby S.	10	10	0
Snell, Sir John	41	9	6
Sparks, C. P., C.B.E.	99	12	0
Sparks, H. C., C.M.G., D.S.O.	55	0	0
Stearn Electric Lamp Co., Ltd.	10	10	0
Stroh, A.	295	7	0
Stuart, Lt.-Col. Sir Andrew	6	6	0
Sullivan, H. W.	26	5	0

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Swan, Sir Joseph, D.Sc., F.R.S.	15	5	0
Swinton, A. A. C., F.R.S.	22	1	0
Taylor, J. E.	6	11	6
Tesla, N.	5	0	0
Thompson, Prof. S. P., D.Sc., F.R.S.	5	5	0
Twenty-Five Club	228	18	0
Varley, C. O.	5	0	0
von Chauvin, G.	5	5	0
Vyvyan, R. N.	14	10	0
Wade, E. J.	5	0	0
Walker, W.	5	0	0
Wallace, R. W.	7	7	0
Wallis-Jones, R. J., Capt., O.B.E., T.D.	12	7	0
Walmsley, R. M., D.Sc., F.R.S.E.	7	7	0
Walrond, T. C. T.	39	7	6
Warner, G. W.	10	10	0
Warwickshire Royal Engineer Volunteers	30	0	9
Watson, C. G.	5	0	0
Wawn, C. J.	6	6	0
Webber, Charles E., Major-General, R.E., C.B.	5	5	0
Western Electric Co., Ltd.	92	10	0
Williamson, A.	5	0	0
Wilson, R. P. C.	21	0	0
Woodward, J. H.	40	0	0
" Z " Electric Lamp and Supplies Co., Ltd.	20	0	0

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OBITUARY NOTICES.

JOHN RICHARD BAINTON received his early training in London and went to Australia about 1889, where for several years he was associated with the representation of Messrs. Woodhouse and Rawson, of London. Later he joined Messrs. Edge and Edge, electrical engineers, of Sydney, and whilst with them constructed and equipped a pioneer electric railway at Brighton-le-Sands, New South Wales. He also introduced the electric lift into Australia, later becoming connected with the Standard Electric Elevator Co., of Sydney. When Messrs. Dick, Kerr and Co. secured the first contract for electric lighting plant for the city of Sydney he became the company's Australian representative, and subsequently was associated with many large contracts. In 1920, arrangements were made by Messrs. Standard-Waygood-Hercules, Ltd. (which the Standard Electric Elevator Co. had become by amalgamation with other concerns) to manufacture heavy electrical and steam machinery in Australia to the designs of the English Electric Co., the Australian company taking the name of the English Electric Co. of Australia, Ltd. Of this company he was a managing director up to the time of his death. As a director of Automatic Telephones (Australasia), Ltd., he introduced the automatic telephone to Australia; and he was also one of the pioneers in the use of motor bicycles and motor cars. He was elected an Associate of the Institution in 1889 and a Member in 1899, and was also a foundation member of The Electrical Association of New South Wales (since incorporated in The Institution of Engineers, Australia), serving as President in 1901 and 1902. He took a keen interest in the local volunteers and at one time commanded the company of engineers responsible for military searchlight work in connection with the defence of Sydney. G. B. C.

FRANCISCO BHERING was born in the State of Minas Geraes, Brazil, on the 1st January, 1867, and adopted as his profession that of a civil engineer. In 1895 he joined the staff of the Brazilian Government Telegraph Department. His promotion was rapid and he became chief of the Sao Paulo District in 1901. In the same year he was appointed Brazilian delegate to the International Telegraph Conference held in London. He served in a similar capacity at the International Wireless Conference of 1912, and, in fact, he may be described as the pioneer of wireless telegraphy in Brazil. In 1916 he was appointed sub-director and in 1920 director of the technical department of the Brazilian Telegraphs, and in 1922 he became director general of the Telegraphs, a position which he held at the time of his death, which took place at Paris on the 13th April, 1924, when he was on a visit to Europe on account of his health. The early land line telegraph system of Brazil followed the coast line, and the wires suffered considerably from corrosion. Dr. Bhering's most important work was the diversion of these lines into the interior through virgin forests. In addition to his other duties, he was requested by the Institute of Brazilian Engineers (of which he was a Fellow) to organize and complete a geographical map of Brazil to commemorate that country's centenary. He was one of the founders of the Engineering College at Sao Paulo, and was Professor of the Engineering College of the Rio de Janeiro University. He was elected a Member of the Institution of Electrical Engineers in 1913. The Municipality of Rio de Janeiro, to honour and commemorate his services, has given his name to the street leading to the Arpoador Wireless Station. R. B. D.

LAWRENCE BIRKS, B.Sc., was educated at Prince Alfred College and at the University of Adelaide, where he obtained his B.Sc. degree with triple honours in 1895. In the following year he was awarded the Angas Engineering Scholarship, which entitled him to three years' training in Great Britain. This period was spent at University College, London, and in the workshops and test departments of Messrs. Easton, Anderson and Goolden, of Erith, and of Messrs. Callender's Cable Co. He served for a time as lecturer in electrical engineering under Prof. Silvanus Thompson at Finsbury Technical College, and also as assistant professor of engineering at Heriot-Watt College, Edinburgh. In 1900 he returned to Adelaide, and, after one session as lecturer in electrical engineering at Adelaide University, was appointed assistant engineer to the Sydney electric tramways in connection with the reconstruction of Ultimo power house and the installation of high-tension underground feeders and substations. In 1903 he was appointed city electrical engineer at Christchurch, N.Z., in connection with the first installation of electric power in that city, the power being derived from the destruction of refuse. In the following year he was appointed lecturer in electrical engineering at the Canterbury College, but after one session he took up the duties of engineer to the New Zealand Electrical Construction Co., a local company formed for the purpose of constructing the Christchurch electric tramways. On the completion of this work he was appointed engineer of Rotorua. In 1910, at the passing of the Aid to Water Power Act, he became assistant to Mr. Evan Parry, chief electrical engineer for the Dominion and, after assisting in the design of, and specifications for, the Lake Coleridge works, was transferred to Christchurch in 1913 to supervise the construction of those works and to manage the commercial side of the undertaking. On Mr. Parry's resignation in March 1919, Mr. Birks was appointed chief electrical engineer to the Public Works Department, when active steps were taken by the New Zealand Government to materialize a comprehensive scheme of power supply planned for the North Island. The

following works were carried out during his period of office, viz. the development of the Mangahai source with transmission lines to Palmerston, Wellington, Wairapa and Hawkes Bay. Preliminary works were carried out at Waikaremoana and Arapuni, and a contract placed for headworks and plant for the latter source. During this period also the power-house plant at the Horahora Falls belonging to the Waihi Gold Mining Co. was taken over by the Government, extended and utilized for the supply and distribution in the Waikato district. In April 1924, he left New Zealand to represent the Dominion at the World Power Conference in London, but on his arrival in Adelaide he was obliged to seek medical advice, as a result of which he immediately returned to New Zealand, where he died on the 25th July at Wellington. His knowledge and experience of all matters pertaining to hydro-electric power development and of distribution systems as applied to the general supply of electricity were very extensive. His engineering achievements also were considerable and varied, and one of them deserves particular recognition: the result of his work in Canterbury was to demonstrate to the world at large the commercial possibility and the economic advantage to a State of a generous supply of electricity to every home, not only for light but for every purpose, including water-heating. In character he was energetic and resourceful, open-minded and generous. All his actions bore the impress of high ideals and his life was an inspiration to all who were associated with him. He joined the Institution as an Associate in 1896, was elected an Associate Member in 1899, and a Member in 1912. He was also a Member of the Institution of Civil Engineers, a member of the Institution of Mechanical Engineers and a Member of Council of the New Zealand Society of Civil Engineers. He took an active part in the affairs of the New Zealand Institute, and was one of the sub-editors of the *New Zealand Journal of Science and Technology*.

E. P.

CHARLES EUGENE L. BROWN died at his home in Montagnola, near Lugano, on the 2nd May, 1924, at the age of sixty-one, from heart failure following a short illness. He was born in Winterthur on the 17th June, 1863, being the son of the late Mr. Charles Brown, who was mainly responsible for the Sulzer drop valve-gear. After a year as improver with Burgin in Basle, he entered the Oerlikon Machine Works and two years later, when barely 24 years old, became manager of the electrical department. His early years at Oerlikon were occupied in developing a direct-current system and in designing commercially workable direct-current machinery. His first machines were of the two-pole Manchester type with ring armatures, and for the first power transmission in Switzerland (Kriegstetten-Solothurn, 37 kW over five miles) machines of this type were employed. By successive stages in development, four-pole designs with slotted drum armatures were arrived at, which (contrary to the usual practice at that time) were distinguished by relatively large magnetic fluxes and a small number of armature conductors, so that even machines for 600 volts had but one turn per segment and sparkless commutation was ensured. Among the early power plants which he constructed may be mentioned the Neuhausen plant, the 6 000- and 12 000-ampere machines for which remained for long the largest direct-current dynamos in Europe; those for 12 000 amperes had vertical shafts, and multiple series-parallel winding was used for the first time. He employed for his first alternating-current transmissions single-phase generators and synchronous motors, which were of the Kapp ring-armature type, and these were the first machines provided with direct-coupled exciters. The practical development of the polyphase motor was realized during the year 1890. Simultaneously with Dobrowolski he originated the polyphase winding with rectangular coils in slots (in practically its present-day form), whereby magnetic leakage is so far reduced that a sufficiently high starting torque can be reached. Later on, he used for the first time the distributed winding in slots for the stators and rotors of the larger polyphase motors. The year 1891 brought the opening of the Frankfort Exhibition and the celebrated power transmission from Lauffen to Frankfort (110 miles) with three-phase current at 25 000 volts, this effectively demonstrating the technical possibility and commercial feasibility of the transmission of power over great distances by electricity. He designed for this power transmission (the failure of which was confidently predicted in electrical circles at that time) the 40-pole generators with claw pole-wheel and single exciter coil and oil-cooled 86/25 000-volt transformers. The latter —the first oil-immersed transformers—were made with three cores situated at 120° to one another, connected above and below by a round yoke, and for them was used for the first time the double concentric winding. In 1891, in association with Mr. W. Boveri, he founded the works of Brown, Boveri and Co., Baden, Switzerland, many of whose present-day designs bear the impress of the original ideas of the technical founder of the firm. The high position in the construction of single-phase and polyphase machinery to which he brought his firm by means of his inventions and designs became apparent in 1894 when eight alternators (four of 525 kW and four of 1 050 kW running at 85 r.p.m.) were built for the city of Frankfort in face of great competition from German firms. From the year 1895 onwards the development of many Swiss water powers was actively carried out, and for the vertical units called for by the low falls the umbrella type of generator was designed (1897). Two years earlier he had constructed the first flywheel generators with pole-wheels rotating outside the stationary armatures. In 1896 were built the 8 000-volt generators for Schwyz, while in 1898 the noteworthy 14 500-volt generators for Paderno were constructed. In the electric railway field the Lugano tramway, installed in 1894, was the first traction system for which three-phase motors were used, and this was followed by many mountain and other polyphase railways, which are all in successful operation at the present day. The acquisition by his firm in 1900 of manufacturing licences under the Parsons steam-turbine patents turned his thoughts to some of the special problems due to the introduction of high-speed machinery, and he soon recognized that for turbo-alternators

of large outputs and high peripheral speeds the construction with projecting field-poles could not be satisfactory. This led to the creation of the generator rotor in the form of a cylinder with radial or parallel slots for carrying the excitation winding, which has proved to be the only possible constructive solution and has been universally adopted. In the direction of switch and control gear many original designs were developed, amongst which may be mentioned the multiple-break oil circuit-breaker and the so-called "horn" arrester. After the conversion of the firm of Brown, Boveri and Co. into a limited company in 1900, he became chairman of the board of directors and held that position until 1911, when he retired altogether from his business and technical activities. In 1912 he was awarded the honorary degree of Doctor by the Technical College of Karlsruhe. He was elected a Foreign Member of the Institution in 1892 and became a Member in 1911. A. C. E.

SIR ALBERT J. LEPPOC CAPPEL, K.C.I.E., died on the 20th April, 1924, in his eighty-eighth year. He was one of the dwindling band of men who saw service in the Crimea, having served with the Turkish Contingent in 1855–6. In 1857 he entered the Indian Telegraph Service, then in its infancy, becoming Director of Traffic in 1869, Deputy Director-General in 1879, and Director-General four years later. He held the position for six years before retiring, and saw the department expand almost beyond recognition of the earlier days. In February 1887 the knighthood of the Order of the Indian Empire was conferred on him, and at the time of his death he was the senior holder of that rank. Sir Albert's interest in telegraphy did not cease with his retirement from India. For much more than a quarter of a century after his retirement from the Indian Telegraph Department he was actively interested in the work of the Eastern and Associated Telegraph Companies. He joined the Board of the Eastern Telegraph Company in 1888, and in the following years became a director of the other companies of this group. He was also a director of the Globe Telegraph and Trust Company, and a trustee of the Submarine Cable Trust. He gave his whole heart to this work, and was almost daily in attendance at the offices of the cable companies up to within a few days of his death. He was elected a Member of the Institution in 1878, and served on the Council in the years 1900–1902. H. J. L. C.

COLONEL GEORGE ANDERSON CARR, late R.E., who died on the 20th March, 1924, was one of the pioneers of electrical science in the British Army. Born in 1857 at Nymans, near Crawley, Sussex, he was educated at Uppingham and at the Royal Military Academy, Woolwich. He received his first commission as a lieutenant in the Royal Engineers in August 1876 and, after the usual two years' course of instruction at the School of Military Engineering, was posted to the Submarine Mining Service. Here he came into contact with a little group of Royal Engineer officers who were studying and developing the application of electricity to military purposes. Of these, the best-known to the general public were Major R. Y. Armstrong, R.E., Lieut. P. Cardew, R.E., and Lieut. (now Major-General Sir R. M.) Ruck. Working under and with these officers, he soon found his life work. Not only did he show a great mastery of detail, but he early proved his capacity as a lecturer. Possessed of a remarkable gift for clear and accurate thinking, he was able to explain his thoughts in simple language. With these qualifications it was inevitable that much of his life should be spent in instructional appointments in the electrical branch of the School of Military Engineering and in the School of Submarine Mining at Gillingham, and he held in turn every grade of such appointments at both these establishments. He was for many years the Examiner in Electricity at the R.M. Academy, Woolwich. Among other subjects with which he dealt were the training of army telegraphists and the design of telegraph stores, also the shutter board and test room and all stores used in the submarine mining service and for defence electric lights. In his various capacities as instructor or assistant instructor he was an *ex officio* member or associate member of the Royal Engineers Committee which deals with all patterns of military stores, and he served on all the electrical sub-committees and many special sub-committees of that body. He represented the War Office at the original trials of the Marconi system and formed a personal friendship with Signor Marconi. He became an Associate of the Institution in 1882, served on the Council in 1895-6, and was elected a Member in 1896. W. B. B.

WILLIAM CHEW was born in Manchester in 1855, moving in 1863 to Blackpool, where he joined his father at the gas-works a few years later. In his early days, although attached to the gas industry, he took a keen interest in the development of electricity. He was responsible for the introduction of electric lighting into Blackpool and held the dual appointment of electrical engineer and assistant gas engineer until 1893, when, owing to the growth of the undertakings, it became necessary to separate the two departments. He succeeded his father in 1913 as manager of the gas-works. He was always proud of the fact that he was the first to light a seaside esplanade in this country with electric arc lamps. These were on 9 steel masts each 50 ft. high, and each lamp was run from a separate dynamo. Although continuing in the gas industry he took a broad-minded view and quickly introduced electric power where it could be advantageously used in the gas-works. He died on the 9th April, 1924. He was elected a Member of the Institution in 1893. J. H. C.

DAVID COOK was born in 1856 near Lochranza, in the Isle of Arran, Scotland, and died at Richmond on the 23rd July, 1924. From an early age he was keenly interested in electricity, and from the beginning of 1881 was engaged exclusively in electrical work. Up to the end of 1883 he was connected with the Edison Electric Light Co., Ltd., and on the amalgamation of this firm with the Swan United Electric Light Co., Ltd., he was responsible for their work in Scotland until February 1885. From March 1885 to February 1886 he was associated with

the firm of Muir and Mavor, Glasgow, and for several years subsequently he practised as a consulting engineer. In 1889 he was appointed consulting engineer to the Associated Fire Insurance Companies, and was later chosen, chiefly on the recommendation of Lord Kelvin, to become superintending electrical engineer for the Glasgow Corporation. Subsequently, again on the recommendation of Lord Kelvin, he acted for some time—with conspicuous success—as chief engineer and general manager of the City of London Electric Lighting Company. He was later associated with Cecil Rhodes in a vast scheme for growing in the Sudan the entire supply of cotton for the needs of Great Britain. This scheme was to be carried out by regulating the flow of the Nile as it issues from the Great Lakes, but was, for various reasons, not proceeded with at the time. The Government have since, however, advanced a sum of £3 500 000 to enable it to be commenced. His later activities were connected with engineering and development schemes both at home and abroad. He was elected a Member of the Institution in 1890. A. D.

ROWLAND EDWARD DIXON was born on the 20th October, 1872. He received his early education at private schools and from 1887 to 1890 attended Stanley Hall, Wakefield. From there he went to Yorkshire College, Leeds, and to the Polytechnic, London. From 1892 to 1895 he was apprenticed to the firm of B. Verity and Sons, Covent Garden (now Veritys, Ltd.), and at the end of this period he became a director and chairman of Messrs. S. Dixon and Sons, Leeds, electric lighting and power contractors and manufacturers of overhead line materials for tramways and also of patent point controllers for tramways, etc. He remained with this firm until his death, which occurred after a short illness, on the 28th November, 1923. He was elected an Associate of the Institution in 1895 and a Member in 1913.

ARTHUR EDGAR GOTT was born in Sunderland, where he received his early education, his technical education being obtained at the Rutherford College of Science, Armstrong College, and Manchester Technical School. He served his apprenticeship with Messrs. Weedon and Irish, of Sunderland. He then went to the works of Messrs. J. H. Holmes and Co., and carried out the electrical installations on a number of ships and in various mills and factories. He was with this firm 16 years, the last 7 years as senior assistant engineer. He then joined Messrs. Veritys as manager of the controller and switchboard department, a position which he held for five years. After a short engagement with the J. L. Manufacturing Co., of Southall, he went as engineer-representative to the British Petroleum Co. in connection with the application of liquid fuel in manufacturing processes. He later spent two years with the Waddle Patent Fan and Engineering Co. At the outbreak of war he joined the Sperry Gyroscope Co., acting chiefly as patent expert. He was the author of the Sperry gyro-compass instruction book used by the British and Allied Navies, and drew up the lecture charts and syllabus for the various Compass Schools of these Navies. He was also instructor to naval officers in the use and maintenance of the gyro-compass. He died on the 18th December, 1923, at a nursing home near Bedford at the age of 57, after being for nearly three years in failing health brought on by overwork during the war. He was elected an Associate Member of the Institution in 1901 and a Member in 1919. H. A. G.

ARCHIBALD ERNEST GRANT was born at Swansea on the 1st May, 1870, and was educated at St. Andrew's College, Swansea, where he gained distinction in mathematics and also excelled at football and swimming. On leaving school he served his apprenticeship as a mechanical engineer with the Globe Dry Dock and Engineering Co., and after going to sea obtained his "Extra Chief" Certificate as a marine engineer. He then studied electricity and, in August 1901, obtained an appointment in the contract department of Messrs. British Insulated and Helsby Cables. After four years' experience in the laying and jointing of high-tension and low-tension cables and in the construction of electric tramways, including the laying of the track and the erection of the overhead equipment, he was appointed in 1905 to take charge of the company's sales agency in South Wales. In July 1913 he was promoted to represent the company in Canada and subsequently, in February 1916, became their principal representative in India. He returned to this country in June 1923 and died suddenly on the 29th November, 1923. He was elected an Associate of the Institution in 1901, became an Associate Member in 1903, and a Member in 1916. B. W.

ROBERT FRANCIS HAYWARD, who died in London on the 10th April, 1924, was born in 1865 and was educated at Harrow School, passing thence to University College, London, where he held the Gilchrist Engineering Scholarship. After serving his apprenticeship with Messrs. Crompton and Co. at Chelmsford, he became their works manager in 1890, and left in 1894 for the United States to take up the position of general manager of the Salt Lake and Ogden Gas and Electric Light Co. In this capacity, and subsequently as chief engineer of the Utah Light and Railway Co., he was responsible for a considerable amount of pioneer work in connection with high-tension transmission. In 1905 he left the United States to join the Mexican Light and Power Co. in Mexico City as their general manager, and the four years for which he remained with this company was a period of great development of their hydro-electric system, which is now one of the largest in Latin America. From 1909 until 1920 he was chief engineer and general manager of the Western Canada Power Co., furnishing bulk power to the British Columbia Electric Railway Co. and the Vancouver district generally from a 40 000-h.p. hydro-electric plant at Stave Falls. When the control of the Chilian Electric Tramway and Light Co. and the Cia. Nacional de Fuerza Electrica passed to the S. Pearson and Son interests, and the Cia. Chilena de Electricidad was formed, he was appointed general manager and occupied that position until a few months before his death. This covered three years of intense

construction activity, including the transformation of the whole distribution system of the city of Santiago, the erection of 110 000-volt transmission lines from the Andes to Santiago and Valparaiso, the addition to the system of a 35 000-h.p. hydro-electric plant, and considerable extensions to the steam station. He was of the best type of travelled Englishman, possessing a charming personality, wide knowledge, and a sterling character, and will be greatly missed by a host of friends in all the countries to which his work took him. He was elected a Member of the Institution in 1912.

S. G.

WILLIAM DODS HUNTER served his apprenticeship with Messrs. Clarke, Chapman and Co., and later was employed by Sir Charles Parsons. In 1889 he became engineer to the Newcastle and District Electric Lighting Co., Ltd., and was later appointed managing director and engineer. He did a great deal of strenuous work during the war and never quite recovered from the effects, being compelled in 1918 to retire from active management. He remained on the directorate, however, and gave the benefit of his knowledge to the company. He died on the 17th May, 1924. He was elected a Member of the Institution in 1892, and for many years served on the Committee of the North-Eastern Centre, of which he was chairman from 1900 to 1905.

GORDON LAYTON received his early education at private schools at Birchington and Luton. On leaving school in 1897 he was apprenticed to the Electrical Power Storage Co. At the end of his apprenticeship he joined the London Electric Cab Co., where he was in charge of the generating station and the high-tension substation. In 1899 he became associated with the Westinghouse Co. and was sent to the Westinghouse works at Pittsburg to study American methods. On his return he worked in the correspondence department, of which he later became the head. He was subsequently transferred to the sales department and became manager of the Manchester district office. He afterwards returned to the works and was appointed manager of the district offices. On account of failing health he found it necessary to go abroad and he took up a position with the company in South Africa. He afterwards returned and became manager, and later managing director, of the Cosmos Lamp Works, which position he held until his death on the 31st January, 1924. He was connected with the promotion of the Engineers' Clubs at London and Manchester. He was elected a Student of the Institution in 1897, an Associate in 1900, and a Member in 1912. From 1907 to 1910, and from 1911 to 1914, he served on the Committee of the North-Western Centre, of which he was vice-chairman in 1914–15.

MAURICE LEBLANC was born in 1857 and received his technical education at the École Polytechnique in Paris. At the conclusion of his studies in 1878 he joined the Compagnie des Chemins de Fer de l'Est and in 1886 was associated for a short period with an industrial company. In 1888 he commenced a series of researches on electrical apparatus, which included compound alternators, transformers, rotary converters, frequency changers and phase advancers, the last-named of which he claimed to be the first to produce. In conjunction with Hutin he introduced the damping device known as the amortisseur. In 1897 the General Electric Company of America offered him the post of Engineer-in-Chief, but he did not accept it. In 1901 a number of his electrical patents were purchased by Mr. George Westinghouse for the Westinghouse Electric and Manufacturing Co. and the General Electric Co. of America. From this time, at Mr. Westinghouse's suggestion, he directed his attention to mechanical engineering problems, particularly in connection with steam condensers, rotary compressors, etc. While engaged in this work he evolved his well-known rotary air pump by which very high vacua are produced. On the outbreak of the European War he took part in the invention of a trench mortar and was instrumental in developing a new aeroplane engine. In later years he put forward a proposal to utilize high-frequency currents for the propulsion of electric railway trains. He was a director of the Hewittic Electric Co. and consulting engineer to the Société Anonyme Westinghouse. During the years 1912–14 he was President of the International Electrotechnical Commission, and in 1918 was elected the first member of the Industrial Section of the Académie des Sciences. He died on the 27th October, 1923, at the age of 66. He was elected an Honorary Member of the Institution in 1915.

JOHN ST. VINCENT PLETTS was born on the 22nd January, 1880, and died at his home at Surbiton on the 26th April, 1924, after a short illness. He received his general education at the Isle of Wight College and in 1896 went to the Central Technical College, in the department of electrical engineering, where he stayed for three years. He then joined the Marconi Wireless Telegraph Co. and was engaged in erecting wireless stations for the company in Hawaii, Labrador, the Congo, Russia and the Far East. From 1910 until 1919 he was head of the company's patent department. In the capacity of consulting engineer he was their expert in all legal cases on patents relating to wireless telegraphy, including the well-known "7777" case and the "Mullard valve" case. He was a member of various technical societies and a writer of technical articles, in addition to being the inventor of a slide rule and a cryptograph machine. During the war he acted as expert in cryptography at the War Office. He was a very reserved man and, though holding a prominent position, was very unostentatious and considerate towards those who worked for him. He was elected an Associate of the Institution in 1902 and a Member in 1919.

WILLIAM STEWART ROBERTSON died on the 1st September, 1924, in his seventieth year. His connection with telegraphy commenced in 1873 when he entered the service of the Post Office at Edinburgh. Five years later he was selected for service under the Japanese Imperial Telegraphs. On the termination,

in 1884, of his contract with the Japanese Government he obtained employment in the Pouyer Quartier Cable Co. and in 1886 with the Western and Brazilian Telegraph Co. (now the Western Telegraph Co.). He served first at Bahia as an operator, becoming later Assistant Superintendent at Rio. In 1896 he was loaned to the Amazon Telegraph Co. in Para, where he was later appointed Superintendent of the Western Telegraph Co.'s station. He held that appointment until 1904, with a short interval during which he served as electrician on the cable ship "Buccaneer." In March 1904, he was appointed General Superintendent of the Western Telegraph Co. in South America, with headquarters at Rio de Janeiro, and held that position until his retirement in June 1920, after nearly 48 years of telegraph service, during which he saw submarine telegraphy emerge from its preliminary stages and grow into the efficient high-speed service of the present day. Although he had no share in the invention of systems and apparatus which have resulted in the existing improved working of submarine cables, he kept pace with the times and took a prominent and practical part in their application to the sections and stations under his control. He was elected a Member of the Institution in 1898.

DAVID CURLE SMITH was born in Aberdeen and was for five years an apprentice in the Great North of Scotland Railway Co., Aberdeen, also attending the Edinburgh University engineering classes. He then went for two years as assistant to Prof. Jamieson of Glasgow. At the end of this period he joined the Griffen Gas Engine Co., of Bath, as draughtsman, leaving there in 1887 to go to Melbourne, Australia, where he was employed by a leading engineering firm. He was later appointed electrical engineer to the New Australian Electric Co., Melbourne, and subsequently became chief engineer to the municipality of Kalgoorlie. He died on the 28th December, 1922. He was elected a Member of the Institution in 1896.

CHARLES PROTEUS STEINMETZ, who was elected a Member of the Institution in 1912, was born in Breslau, Silesia, on April 9th, 1865. At the time of his death on October 26th, 1923, at the age of fifty-eight, 34 years had elapsed since Carl Steinmetz landed in New York in June 1889 from the steerage of a French liner and adopted America as his country and Charles Proteus Steinmetz as his name. In the preface to "America and the New Epoch" he states that he then "had ten dollars and no job, and could speak no English." Dr. E. W. Rice thus describes his first impressions of Steinmetz :—

"I shall never forget our first meeting at Eickemeyer's workshop in Yonkers. I was startled, and somewhat disappointed, by the strange sight of a small, frail body surmounted by a large head, with long hair hanging to the shoulders clothed in an old cardigan jacket, cigar in mouth, sitting cross-legged on a laboratory worktable. My disappointment was but momentary, and completely disappeared when he began to talk. I instantly felt the strange power of his piercing but kindly eyes, and, as he continued, his enthusiasm, his earnestness, his clear conceptions and marvellous grasp of engineering problems convinced me that we had indeed made a great find. It needed no prophetic insight to realize that here was a great man, one who spoke with the authority of accurate and profound knowledge, and one who, if given the opportunity, was destined to render great service to our industry. I was delighted when, without a moment's hesitation, he accepted my suggestion that he come with us."

Steinmetz's 34 years in America was a period of prodigious performance on his part. In any attempt to obtain a measure of his activities as an inventor, the 195 American patents taken out in his name should be multiplied many times to take into account the inspiration which he communicated to his assistants and colleagues of all ranks and ages. The wide variety of his inventions may be indicated by mentioning the following amongst the subjects of the Steinmetz patents : phase transformation, methods of regulating the power factor of a distribution system, compensated alternating-current motors, magnetite arc lamps, flaming arc electrodes containing titanium carbide, seals for fused quartz lamps, and many patents relating in general to generators, motors, synchronous converters, induction regulators, frequency changers, transformers and measuring instruments. He presented 44 technical papers before the American Institute of Electrical Engineers and was its President in 1901. He also made many contributions to the *Proceedings* of the Illuminating Engineering Society, of which he was President in 1915. He also often contributed notable papers and made important addresses at Conventions and meetings of the National Electric Light Association, at meetings of sections of the American Institute of Electrical Engineers, and of university technical societies. Some of his most fascinating addresses were of a popular character. On one well-remembered occasion when he addressed a large audience in Schenectady at Edison Hall, the subject was "Soap Bubbles." Steinmetz, with one knee on the seat of a chair, blowing bubbles under all sorts of conditions, directed the attention of a fascinated audience to the various phenomena involved. In addition to many engineering papers in the *Transactions* of technical societies, he contributed almost innumerable articles to other publications and on all manner of subjects. We find such titles as : "Physiology of Light," "The Second Law of Thermodynamics and the Thermodynamics of the Atmosphere," "Commission Control," "Competition and Co-operation," "Industrial Efficiency and Political Waste," "The World Belongs to the Dissatisfied," "Socialism and Invention," "Electricity and Civilization," "The Tungsten Gun," "The Ether," "Our Civilization," "Shorthand," "Democracy," "Science and Religion," "Twisting Magnetism," "Biography of Rudolf Eickemeyer," "Electrical Consonance," "Soviet Plan to Electrify Russia," and "Mobilizing Niagara to Aid Civilization." Eleven treatises of a very authoritative character on electrical subjects were published by Steinmetz and the majority of them were revised and greatly extended in several successive editions. Already in 1888 he had published a book on "Astronomy, Meteorology and Cosmogony." The Steinmetz law of hysteresis is well known, as are

also his contributions to the development and use of the complex-quantity method of treating alternating-current problems.

Steinmetz's activities were by no means confined to engineering. He took a very deep interest in human questions and in economics, and gave his cordial support to all movements whose success he considered would be of advantage to mankind. In this category he included the adoption of the metric system. At the University of Breslau he studied mathematics, astronomy, physics, chemistry, medicine and economics. Subsequently at Zurich he studied mechanical engineering at the Polytechnic. In later life, at Union College in Schenectady, he was professor of electrical engineering and afterwards of electro-physics. As the candidate of the Socialist Party in 1915 Steinmetz was elected President of the Common Council of Schenectady. He served two terms as President of the Schenectady Board of Education. In 1902 Harvard University conferred on him the degree of Master of Arts, and in 1903 Union College awarded him the degree of Doctor of Philosophy.

It was the writer's privilege to be much with Steinmetz as one of his assistants in 1892 and the immediately following years, and again to have associations with him in the years preceding his death. In the writer's opinion the best pen-picture of Steinmetz in these later years is that drawn by Mr. M. P. Rice as follows :—

"The unassuming figure without hat or overcoat, that was so well known about the streets of Schenectady, was literally a world power. To him every country looked for authoritative dicta on all matters of electricity. The man who welcomed friends to his summer camp with an almost boyish glee, whose kindly soul went forth in the fondling of a favourite dog, whose life and likings were the most simple—this man was an international figure, a giant in his profession, a conservator of the world's natural resources, and a friend to every user of electricity. We mourn his passing, we are deeply grateful for the wealth of knowledge that he has contributed to the world's progress, and we treasure as a choice possession the memory of an earnest, simple man who devoted his transcendent mind and talents to the service of his fellow men."

For many years Steinmetz had made his home in Schenectady, New York, with the family of Mr. J. L. R. Hayden, his adopted son. Mr. Hayden was his constant companion and also his collaborator in many of his investigations and papers. Their home included a fine library and a well-equipped chemical and physical laboratory, and Steinmetz divided his attention between the home laboratory and various laboratories at the Schenectady works of the General Electric Company of America.

H. M. H.

W. HOWARD TASKER, who was born in 1857 and who died on the 17th September, 1924, was educated at Eastbourne and Guildford and trained as an architect—his father's profession. Dr. Graham Bell's lecture in London on the telephone in 1878 turned Mr. Tasker's thoughts to electrical engineering. He made in his own workshop many models of telephonic and electrical apparatus, and later these models were used when giving evidence in the Law Courts. He worked as an improver in the shops of Messrs. Warner and Lee, mechanical engineers, London, and studied at the School of Submarine Telegraphy and Electrical Engineering, representing it at the first British Exhibition of Electrical Engineering held at the Crystal Palace in 1882. He was assistant electrician to the Yorkshire Brush Electrical Engineering Co. He erected for them, and subsequently managed, the first central electric lighting station at Middlesbrough, supplying electricity to the North-Eastern Steel Works and neighbouring blast furnaces, and while with the Brush Company he advised several local engineering works on their electrical plant. During his career he worked as an engineer for the Primary Battery Co., Ltd., the Fitzgerald Electric Light and Power Co., Ltd., and the Union Electric Light and Power Co., Ltd., and was for many years with the Chelsea Electricity Supply Co., Ltd., which was the first supply company in London to get to work under the Electric Lighting Act of 1886. As resident engineer he carried out for the Brush Company the contract for the supply of electricity at Dover, and he was subsequently connected with the British Westinghouse Electrical and Manufacturing Co., Ltd., and with the Hart Accumulator Co., Ltd. He had a charming personality and was an enthusiast in both work and play. He organized the first bicycle road-racing teams in Surrey in 1875 and 1876 and was a keen lacrosse player, representing the South more than once in the annual North v. South match. He was elected an Associate of the Institution in 1882 and a Member in 1891.

R. T. S.

PAUL SOMMERVILLE THOMPSON was born on the 31st January, 1876, and died after a short illness at Saltburn on the 4th July, 1924. His early education was received at the Rutherford and Armstrong Colleges, Newcastle-upon-Tyne, and he served an apprenticeship with Messrs. E. Scott and Mountain, Ltd., afterwards holding appointments with the Wallasey and Malvern Urban District Councils and acting as assistant mains engineer at Manchester. From 1904 to 1922 he was with the Cleveland and Durham Electric Power and the Newcastle-upon-Tyne Electric Supply Companies, being general station superintendent to the former for a period of about 11 years. During his residence on Tees-side he endeared himself to numbers of young engineers in the electrical supply industry and devoted much of his spare time to the furtherance of their interests. He was an active member of the Tees-side Sub-Centre, serving as its first Hon. Secretary and later as its chairman. He also assisted with the formation of the Electrical Power Engineers' Association, and will be remembered for the part he played in helping to consolidate the Whitley Council policy of that Association. He became an Associate Member of the Institution in 1902 and a Member in 1918.

A. H. M.

HAROLD LYON THOMSON, who died after a short illness on the 13th March, 1924, was one of the earliest electrical engineers. He was the son of the late R. W. Thomson of Edinburgh, to whom the automobile owes so much for his invention of rubber

and pneumatic tyres, and he inherited much of his father's genius for mechanics. In 1880 he went to Crompton's works at Chelmsford at a time when the invention of the electric lamp by Swan and by Edison had made indoor electric lighting a possibility. His first work was in A. P. Lundberg's shop. At that time he showed remarkable facility in designing domestic fittings of all kinds, and a large proportion of the ordinary fittings now used in connection with indoor lighting were then designed by him, in many cases the original form being still in use with very little modification. He was with Cromptons when they carried out at the Law Courts the first large installation of electric light, this installation being completed in 1882. Many of his fittings are still in use and serve to show how little his first designs have been departed from. He was Cromptons' representative in Paris at the first Electrical Exhibition in 1881. In the early days when so much propaganda work in connection with electric light was carried out by means of portable apparatus he was generally to the fore in showing the advantages of the new illuminant. When representing Cromptons at the Vienna International Exhibition he was invited by the then Khedive of Egypt to go to Egypt, originally to develop electrical work in that country, but eventually to become secretary to the Khedive. Gradually he went over to the political side, that being the stormy period when the expedition was arranged for the relief of General Gordon at Khartoum. When at Cairo he became a student of Arabic and Oriental literature, and on his return to this country he became a distinguished Orientalist. Later he was elected to the Westminster City Council, subsequently becoming Alderman, and Mayor in 1912. He was responsible for Westminster being the first city to take up mechanical transport, and he developed it to such an extent that when the war broke out in 1914 he went over to Flanders in charge of a fleet of the Westminster City vehicles. His skill as a mechanic was exceptional and was much remarked on by his friends. Just before his death he was engaged on finishing the miniature set of gold saucepans for the Queen's doll house which has been shown at the Wembley Exhibition. Westminster owes to him many improvements, not the least of which is the daily collection of house refuse. As a man he was universally loved and his place will be found a difficult one to fill. He was elected a Member of the Institution in 1898. R. E. C.

EDGAR LESLIE THORP was born on the 3rd June, 1874, and was the son of the late Rev. T. Moorhouse Thorp, Wesleyan Minister. He was educated at Kingswood School, Bath, and later at the City and Guilds Institute (London). For many years he was associated with Messrs. Shepherd and Watney, consulting engineers, of Leeds, leaving that firm in 1899 to undertake private consulting work at Nottingham and later at Edenfield in Lancashire. During this period he carried out research work in electrolytic bleaching and wrote a textbook on the subject. In 1912 he returned to Messrs. Shepherd and Watney and on their retiring from the business in 1918 came into possession of it. From that time he was principally engaged in the preparation and carrying out of schemes for all classes of electrical installations, mechanical and hydraulic work, heating plants, etc. His health became affected by incessant toil, but he still struggled on, especially anxious to complete the electrical installation at Marlborough College. He took a special interest in the artistic side of his work and derived much satisfaction from the ingenious treatment of the illumination of the College chapel. The work was almost completed when he had at last to give in. He died on the 21st September, 1923, at the age of 49. He was elected an Associate Member of the Institution in 1899 and a Member in 1920. N. D. T.

ROBERT MULLINEUX WALMSLEY, D.Sc., F.R.S.E., who was elected an Associate of the Institution in 1884 and a Member in 1890, died on the 15th June, 1924, as the result of a street accident which occurred two days previously and for which no one was to blame. He was a pioneer in the vast fields of electrical enterprise which were opened up during the eighties of last century, but was chiefly a distinguished educationist who sought to weld the industries with the higher training institutions and university technical colleges. This desire for unification of the whole structure of technical industry was perhaps reflected in the "sandwich system" of training at the Northampton Engineering College in Clerkenwell and in the affiliation of the College to the University of London. Certainly he did much to eliminate the false distinction between "theory" and "practice" and to dignify the term "Academic"—too often used with indulgent contempt. His ruling passions were the Northampton Institute, of which he was principal for nearly 30 years, and the University of London, but his interest was extended to widely differing stages and types of education.

Dr. Walmsley was born near Liverpool, where he received his early education. He took his London B.Sc. degree in 1882 and, after a short period of teaching experience, became the first senior demonstrator in the electrical department of the Finsbury Technical College under Prof. Ayrton. Continuing under Prof. Silvanus Thompson he took his doctorate in 1886 and in the following year became principal of the Sindh Arts College of Bombay University, where he advised the Government on various educational matters. In 1888 he became senior mathematical lecturer under Prof. Henrici at the City and Guilds Engineering College, and from 1890 to 1895 was the first professor of electrical engineering at the Heriot-Watt College, Edinburgh. In 1895 he was appointed the first principal of the Northampton Polytechnic Institute and with characteristic energy and enthusiasm began the immense task of building up from small beginnings one of London's greatest technical institutes. He was deeply interested in the progress of technical optics and was chairman of important optical bodies. Space does not permit a detailed account of his manifold educational activities. In connection with his work in the University of London, he was chairman of numerous senatorial committees of the University Extension Board, of the Board of Studies in Electrical Engineering,

and of the Board of Examiners, the culmination being his appointment as Chairman of Convocation.

His distinctively electrical work began in his Edinburgh days when he was consulting engineer for the electric lighting of several important Scottish buildings. His writings include "The Electric Current" (1894) and "Electricity in the Service of Man," which began as a revision of Dr. Urbanitzky's book and was transformed, expanded and reissued in numerous editions until in 1904 it was completely rewritten and became his own work. In the same year he read before the Institution a paper on "Transatlantic Engineering Schools," the fruit of study during three months spent in Canada and the United States at the instance of the Governing Body of the Northampton Institute. An earlier paper which appeared in the *Journal* dealt with the electrical features of the Edinburgh International Exhibition, 1890. He also collaborated with Mr. C. E. Larard in a paper on "Engineering Colleges and the War" for the Institution of Mechanical Engineers.

As a man Dr. Walmsley's outstanding characteristics were an extraordinary capacity for work; a geniality and humour which kept him a boy at heart, even to the end of his 70 years; a gift of astute diplomacy, most valuable in controversial or administrative affairs, and a kindliness which glowed with unexpected warmth when his imagination was wakened to anxieties or sorrows among those with whom he came into contact. He loved music, of which he had a wide knowledge, and was ever ready to hear or to tell a good joke. Many may see his character in a new light when they realize that his father's premature death left him with eight younger brothers and sisters to bring up. The distinction won by many of them shows his success, but to such strenuous beginnings may be traced the extreme austerity and self-sacrifice of his devotion to the great technical institute which he served so long. Students and others who hold him in affectionate remembrance must feel, as they stand within the walls of the "Northampton," the applicability of Wren's epitaph in St. Paul's Cathedral:—

"Si monumentum requiris circumspice."

R. P. H.-G.

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EXPLANATION OF ABBREVIATIONS.

(P) indicates a reference to the general title or subject of a paper or address.

(p) indicates a reference to a subject dealt with in a paper or address of which the title is not quoted.

(D) indicates a reference to a discussion upon a paper or address of which the general title or subject is quoted.

(d) indicates a reference to a subject dealt with in a discussion on a paper or address of which the general title is not quoted.

A.

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